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SHALLOW BULK ACOUSTIC WAVES
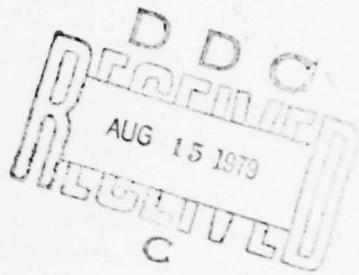
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ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

June 1979

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Crystal resonators	AT-cut quartz	Shallow Bulk Acoustic Waves
Crystal oscillators	Quartz crystals	Bulk Acoustic Waves
Piezoelectric crystals	Frequency control	Surface Acoustic Waves
Piezoelectric vibrators	Frequency-Temperature Characteristics	Doubly Rotated Crystals

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Shallow bulk acoustic wave propagation in piezoelectric crystals is considered from the standpoint of work reported to date. It is compared to bulk and surface acoustic waves as to properties and device potential. Singly and doubly rotated cuts are considered, as are piezoelectric transduction, energy trapping, equivalent networks, as well as areas of future work such as new materials, other than quartz, and nonlinear effects.

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CONTENTS

i

TABLES:

INTRODUCTION

The past forty years have brought about a revolution in frequency control and acoustic signal processing capabilities.[1-66]* The most recent achievements have been due in large measure to the development of surface acoustic wave (SAW) devices[1-7]. These have supplemented, and in some cases taken over various functions formerly performed by bulk acoustic wave (BAW) devices[8], particularly in the area of filtering. At the same time, SAW technology expanded to create entirely new signal processing capabilities based on the availability of the wave as a spatially distributed function at the crystal surface. Bulk wave components, meanwhile, had also found new uses. Foremost among these are new cuts that exhibit compensation of nonlinear elastic effects, leading to resonators that are ultra-stable even under severe environmental conditions. Both BAW and SAW devices profit from the favorable electromagnetic/acoustic velocity ratio which assures significant miniaturization and decreased weight with respect to the corresponding electromagnetic devices.

More recently, attention has been given to a new type of acoustic wave device, utilizing bulk waves that travel nearly parallel to the crystal surface. These are known as shallow bulk acoustic waves (SBAW), or as surface-skimming bulk waves (SSBW), and are the topic of this report. Most of the work reported to date is due to Lewis[9-18] and to Kagiwada[18-28]. Other applicable analyses are due to Mitchell[29], Wagers[30], Jhunjhunwala, et al.[31], and Lee[32].

Of particular importance to the operation of SBAW components is the interdigital transducer (IDT), consisting of interleaved electrode strips, between which the generating electric field is applied via a signal source, or the received field is detected. The IDT array was first applied to the production of BAW signals[33,34], then to SAW devices[35], and finally to SBAW devices[9]. Figures 1 and 2 show, in cross-section, the launching and reception of SAW and SBAW, respectively. Typical energy distributions are also shown; the SAW energy is confined largely within one wavelength of the surface, with evanescent behavior in the direction of the depth. The SBAW, on the other hand, is launched from the IDT array as a shallow beam of energy with real propagation wavenumbers both parallel to the surface and in the depth direction. Without further development, the SBAW device shown would be of little use if the input and output were separated by many wavelengths, because of the large energy losses encountered; fortunately these may be obviated to a large extent as described in a later section.

SINGLY ROTATED CUTS

Crystal cuts are specified[36] by their orientations with respect to the crystallographic axes. A singly rotated cut is one that undergoes one rotation about an axis; a typical example is the rotated-Y-cut shown in Figure 3(a) and denoted as $(YX\ell)\theta$. The most popular such cut is the BAW AT-cut, seen in Figure 4 oriented within a cultured quartz bar. Its success is primarily due to the superior frequency-temperature (f-T) characteristic, which is shown in Figure 5. Also shown in this figure is the curve for the SAW ST-cut which is close in orientation to the AT. For the AT cut, $\theta = +35.25^0$, while for the ST cut, $\theta = +42.75^0$. Another BAW cut, having a zero temperature coefficient (TC) of frequency exists. This is the BT cut, at $\theta = -49.20^0$; its frequency-temperature curve is also shown in Figure 5.

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* See list of references beginning on page 40.

INPUT TRANSDUCER   OUTPUT TRANSDUCER

SAW

ENERGY DISTRIBUTION
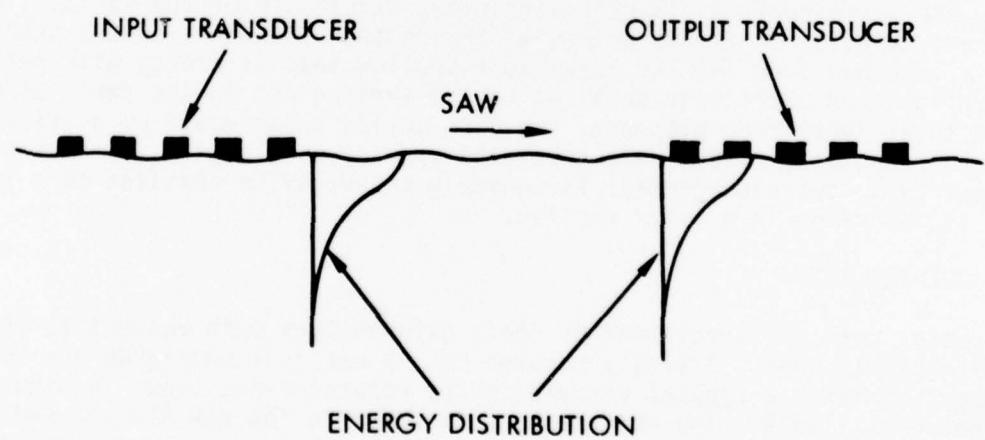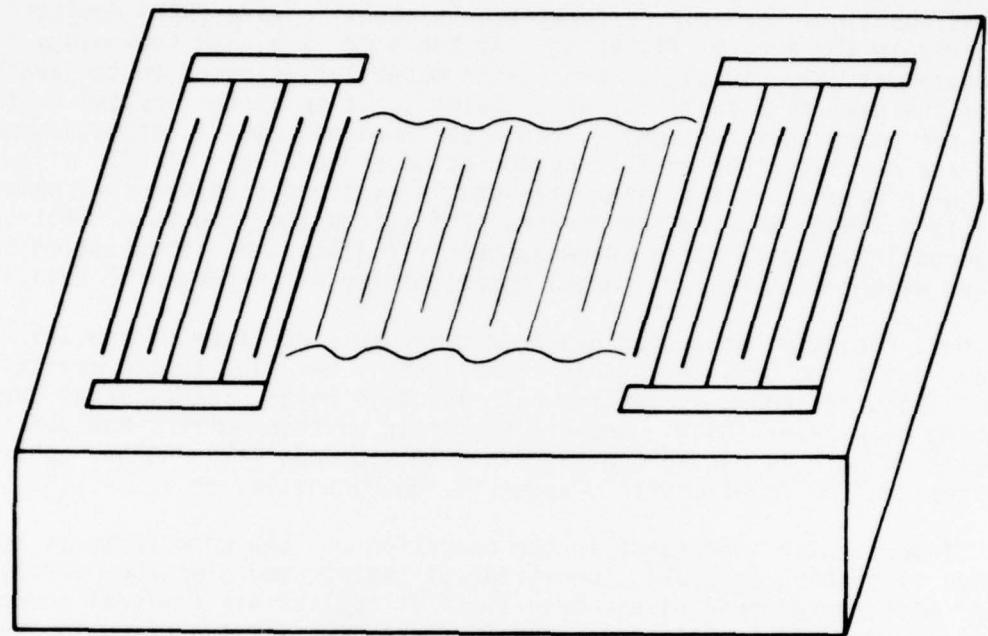
FIGURE 1.   Schematic of SAW Delay Line.

2

INPUT TRANSDUCER

OUTPUT TRANSDUCER

ENERGY DISTRIBUTION
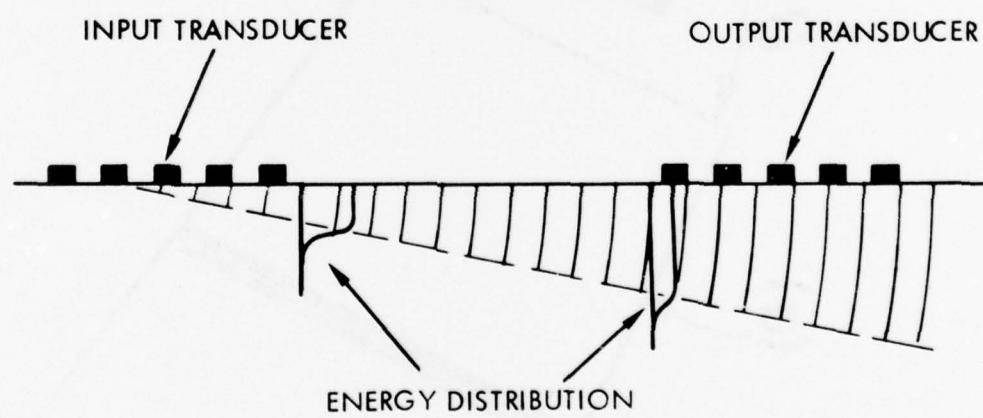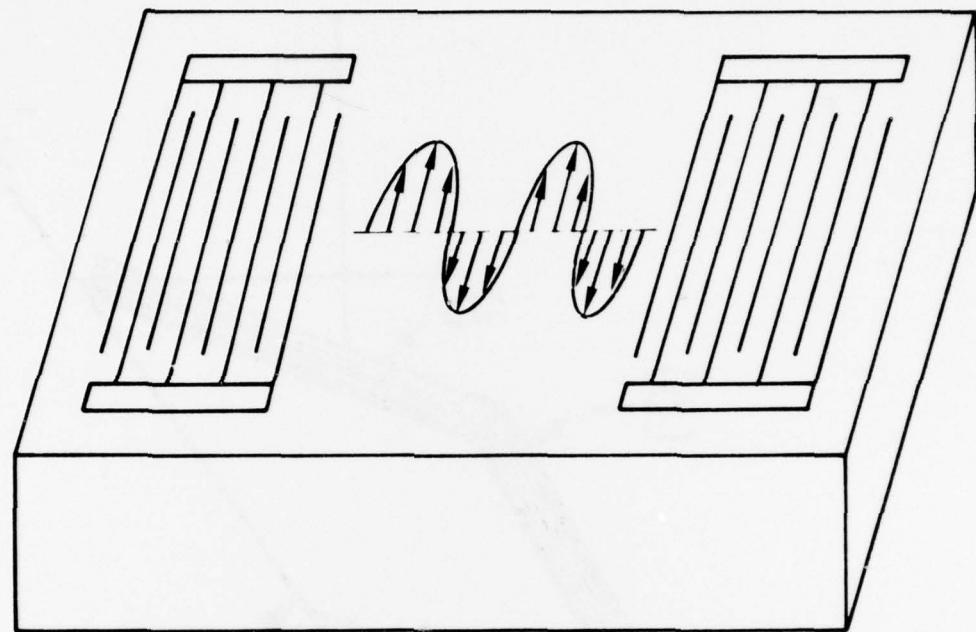
FIGURE 2. Schematic of SBAW Delay Line.

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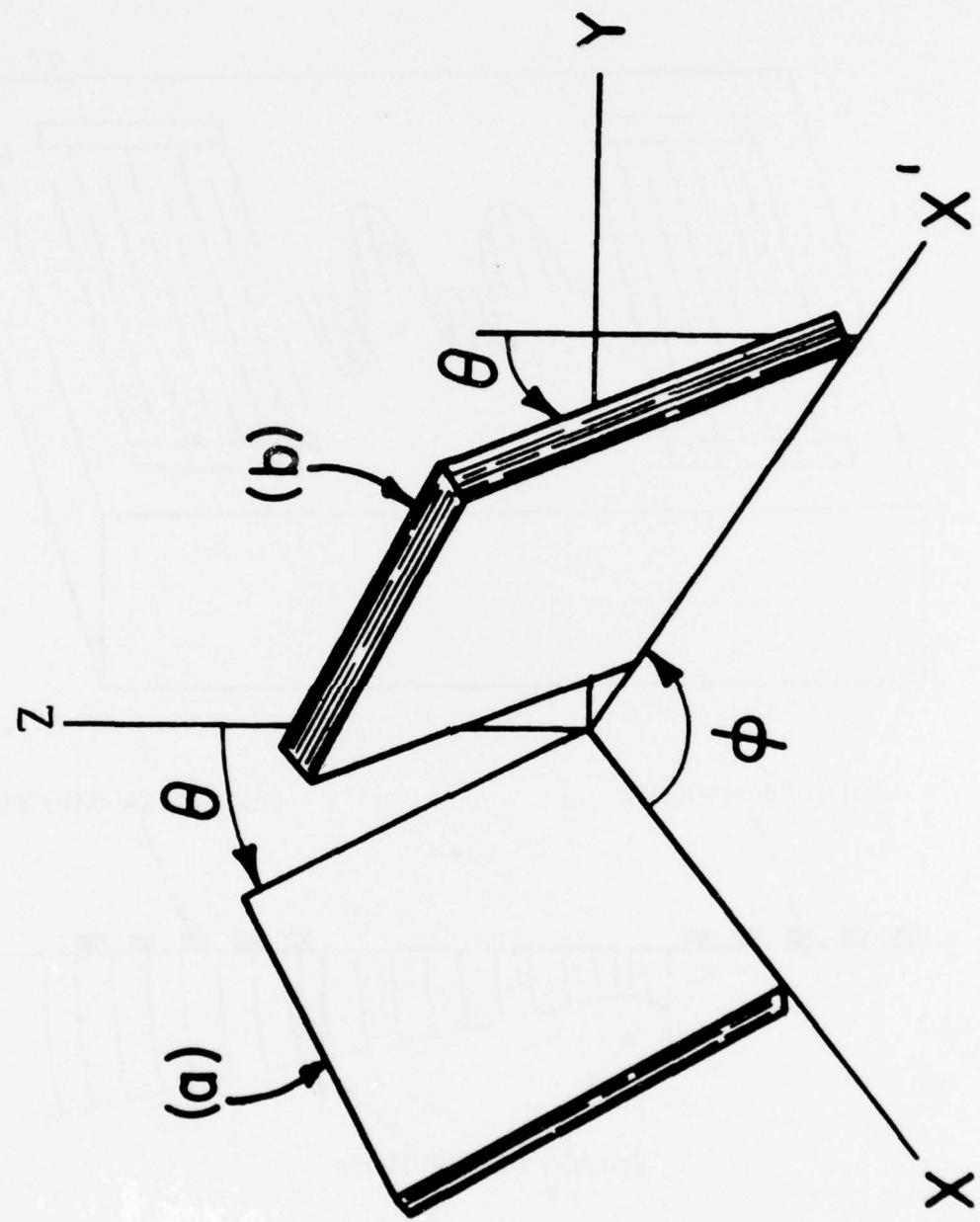
FIGURE 3. Singly (a) and Doubly (b) Rotated Plates.

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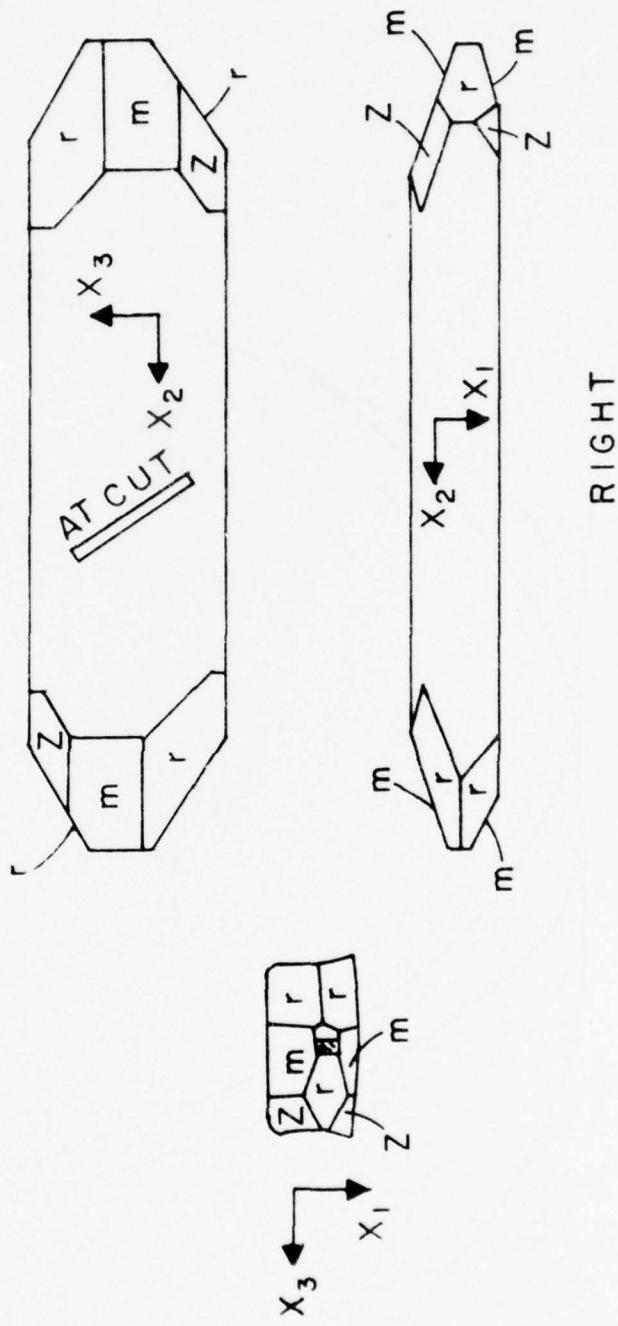
FIGURE 1. Cultured Bar of Right-Handed Quartz.

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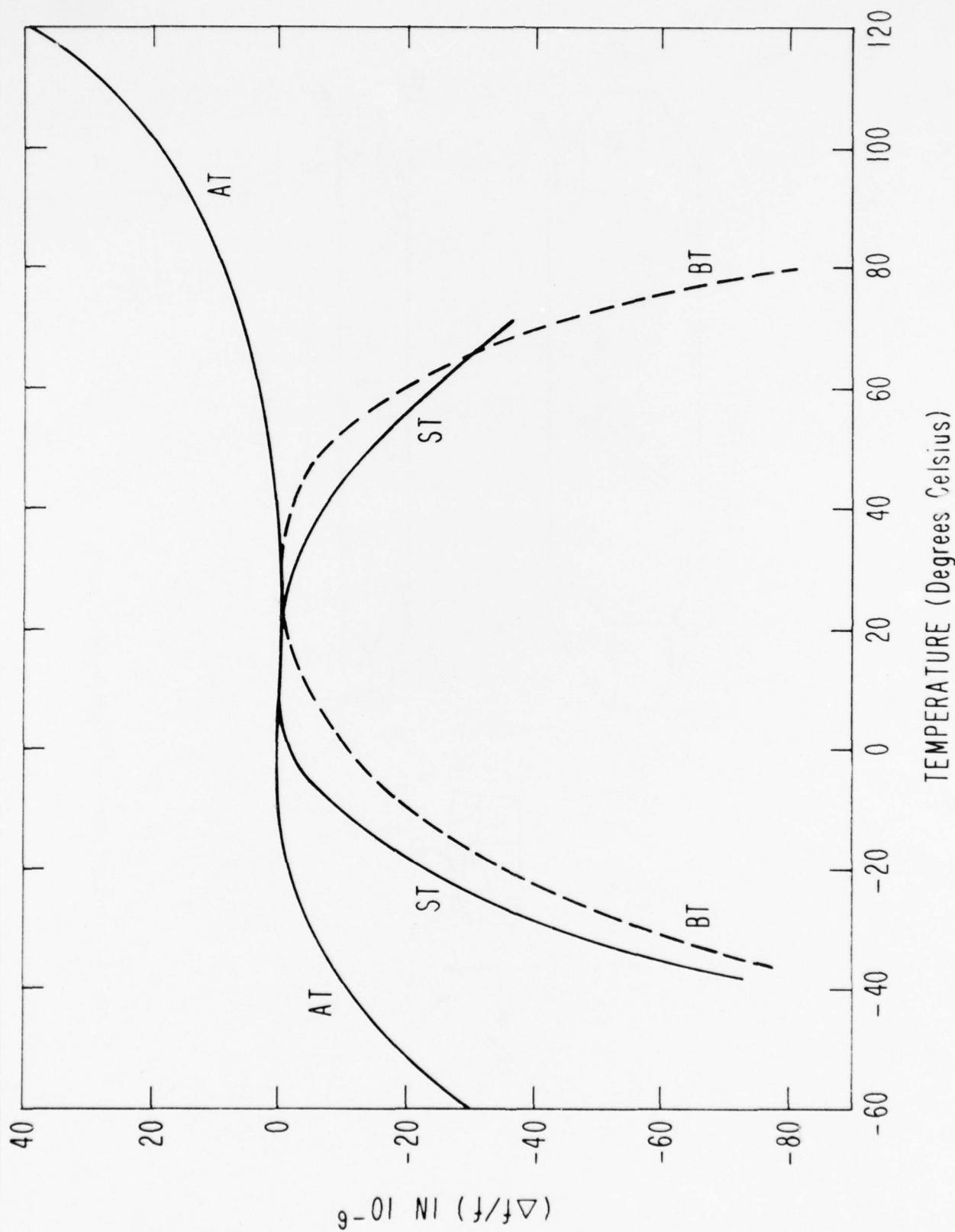
FIGURE 5. Frequency-Temperature Characteristics of Cuts.

When an ST cut, which normally supports SAWs propagating along X_1, has its IDT array turned by $90°$, it produces SBAWs propagating along X_3' (or Z'). The ST cut is nearly perpendicular to the BT cut, so the resulting SBAW has a frequency-temperature (f-T) characteristic very similar to that of the BT cut, because the BT has its BAW propagating in the thickness (X_2') direction. As seen in Figure 5, these f-T curves are parabolic, and not as good as the cubic AT curve.

A big advantage of SBAWs on ST-cut quartz is that the frequency, for a given IDT, is about 1.6 times the corresponding SAW frequency. This ratio depends upon the angle θ, however, and decreases to nearly unity for the BT cut. The ratio can never be less than one because the limiting SAW velocity can never exceed the velocity of the slower shear wave propagating in the X_1 direction for rotated-Y-cuts. This velocity is $\sqrt{c_0/\rho}$, where

$$2 c_0 = \left[(c_{44} + c_{66}) - \sqrt{(c_{44} - c_{66})^2 + 4 c_{14}^2} \right]. \qquad (1)$$

For SBAWs on BT-cut quartz, a compensating feature is the appearance of a cubic f-T characteristic, similar to that of the AT-cut. A family of curves near the BT-cut angle is shown for SBAW propagation in Figure 6; Figure 7 similarly shows the parabolic curves for propagation by SBAW on cuts situated about the AT-cut[13].

Another advantage of SBAWs over SAWs on singly rotated quartz is the absence of SAW generation. When the IDT is arranged for SAW propagation along X_1, BAWs are necessarily produced, as will be seen in a section below; but when propagation of SBAWs take place along X_3', SAWs are not generated. This produces a very clean mode spectrum for SBAW devices.

Lewis[11],[17] also investigated SBAWs on rotated-Y-cuts of lithium tantalate ($LiTaO_3$), but found that, although there was no coupling to SAWs in crystals of class 3m, all cuts of this family had bad TCs. Because of the very large piezoelectric coupling in lithium tantalate, it is useful in wideband filter applications despite its temperature behavior. Examples of this were shown by Kagiwada[23] for lithium tantalate and lithium niobate.

Based upon current work on singly rotated cuts supporting SBAWs, particularly on quartz, the key features summarized in Table 1 are now apparent. In Table 2 are given SBAW capabilities that have been demonstrated in the laboratory to date. It appears that devices based upon the SBAW principle may very well find significant applications as follows:

- delay lines
- resonators
- bandpass filters
- oscillators
- synthesizers

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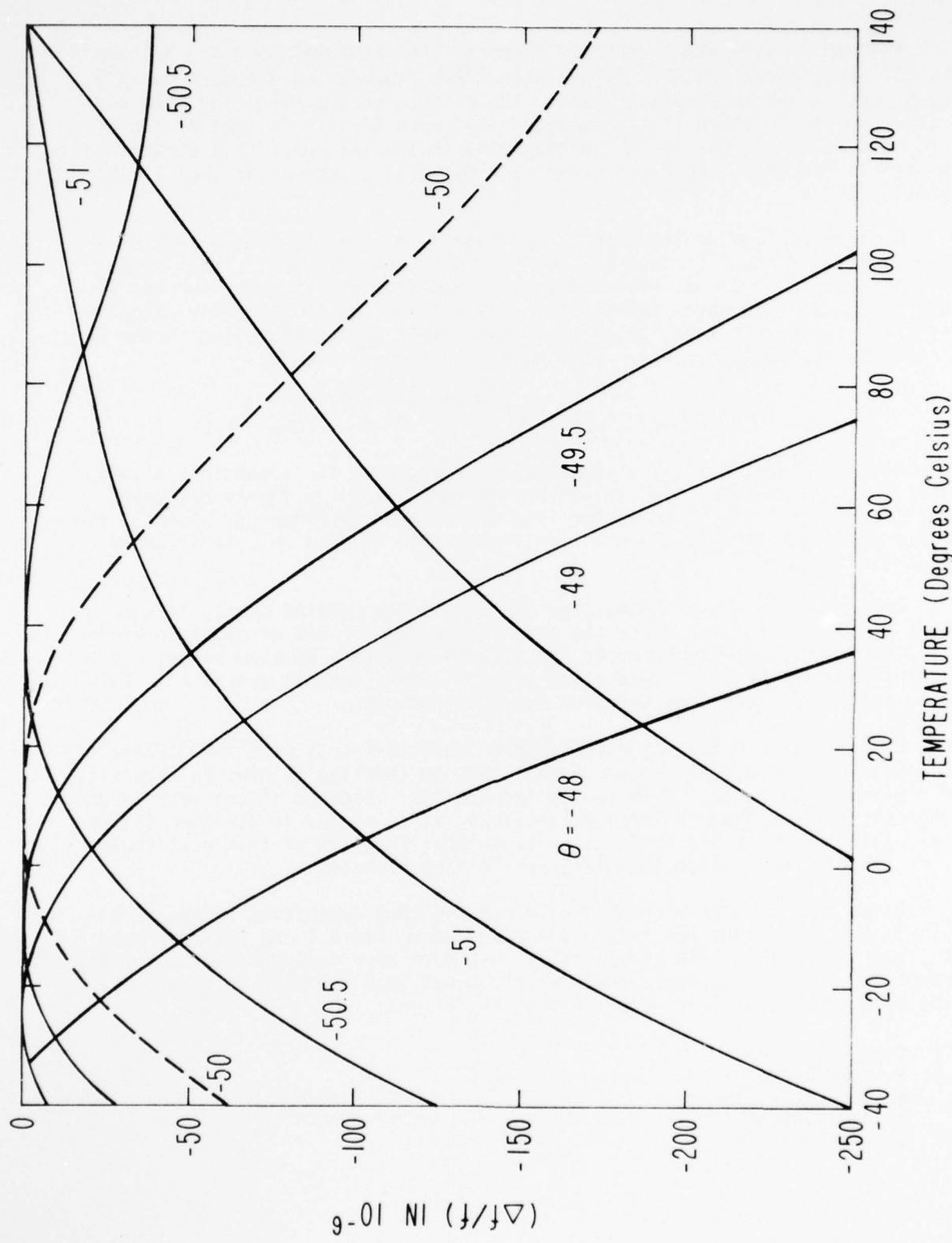
FIGURE 6. Frequency-Temperature Curves for BT-Cut Family.

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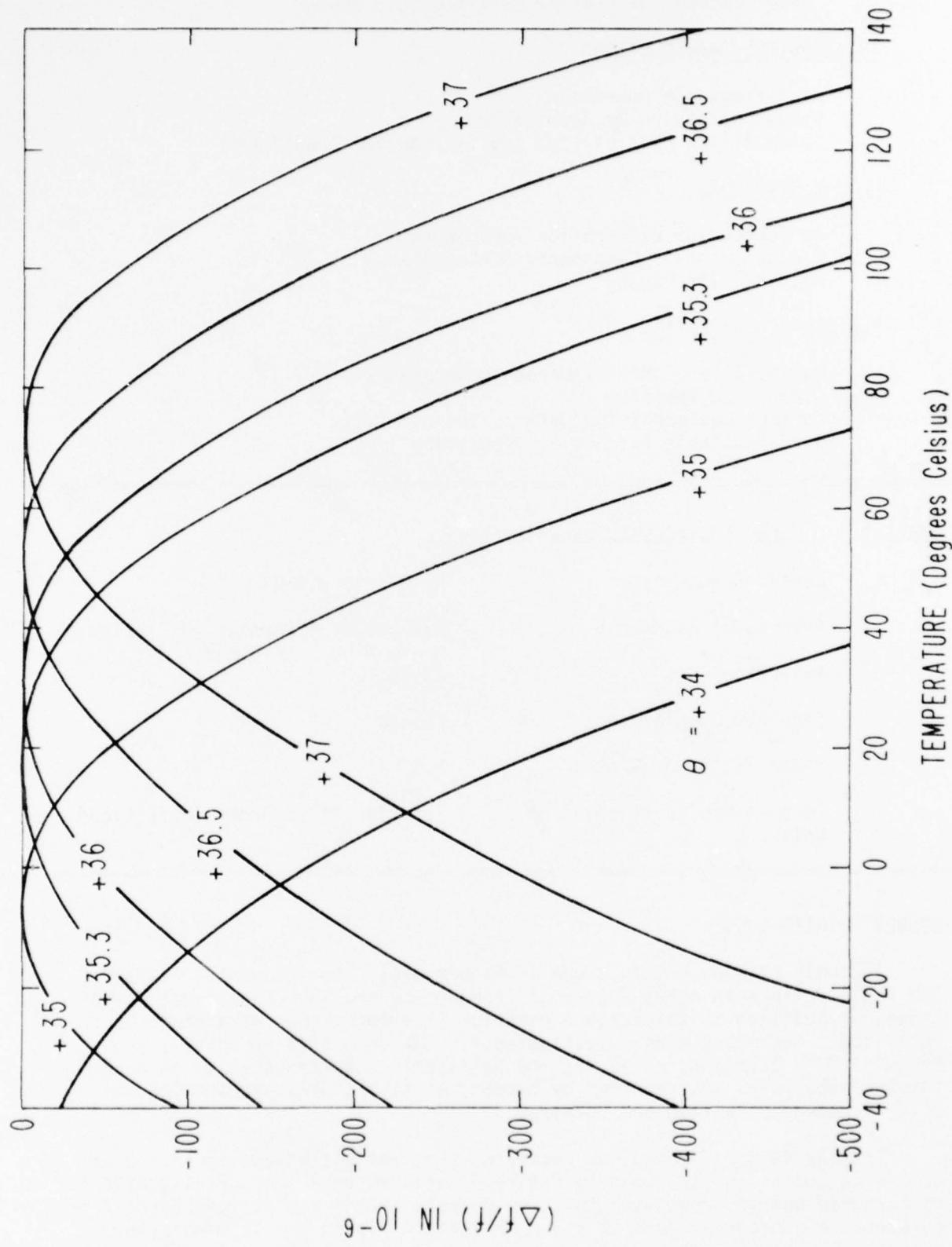
FIGURE 7. Frequency-Temperature Curves for AT-Cut Family.

9

TABLE 1.   Key Features of Shallow Bulk Acoustic Waves

INTERDIGITAL TRANSDUCTION

    High Frequency Operation
    Response Shaping By Apodization
    Large Design Flexibility; Spatial Fourier Transforms

PLANAR STRUCTURE

    Semiconductor Fabrication Techniques
    Microelectronic Components/IC-Compatable
    Mechanically Rugged

PERFORMANCE POTENTIAL

    Parabolic or Cubic Temperature Behavior
    Clean Mode Spectrum
    Surface Contamination/Defects Insensitivity
    Wave Available for Signal Processing

TABLE 2.   Demonstrated SBAW Capabilities

Center Frequency	60 MHz to 2.3 GHz
Fractional Bandwidth	0.3% to 2% (Quartz); 15% (LiTaO$_3$)
Insertion Loss	13 dB
Sidelobe Suppression	>55 dB
Shape Factor 3 dB/40 dB	1.4
Temperature Coefficient of Delay	Zero for First Order Coefficient

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DOUBLY ROTATED CUTS

A doubly rotated cut is shown in Figure 3(b). It is denoted $(YXw\ell)\emptyset/\theta$. The angle $\emptyset$ gives an extra degree of freedom and provides additional advantages; in addition to temperature behavior it allows other parameters to be optimized. Such cuts were investigated for BAW on quartz by Bokovoy and Baldwin[37-39], Bechmann, et al.[40], and Ballato[41]. SAW propagation on doubly rotated substrates was reported by Hauden, et al.[42]; SBAW propagation was briefly noted by Ballato and Lukaszek[43].

The BAW doubly rotated cut receiving the greatest attention at present is the SC cut[41]. It is shown in Figure 8 outlined on a line drawing of a bar of cultured quartz grown such that the $\emptyset$ angle ($\approx 22°$) has already been incorporated. A photograph of such a bar is seen in Figure 9. In manufacture, only the θ angle (approximately that of the AT cut) need be critically adjusted.

10

RIGHT—HANDED   CULTURED QUARTZ
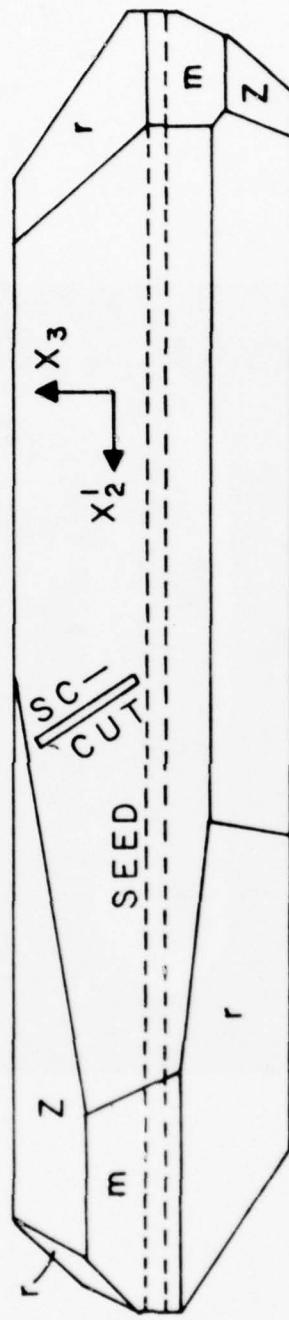
SC — BAR

FIGURE 8. Line Drawing of SC-Bar of Cultured Quartz.

11
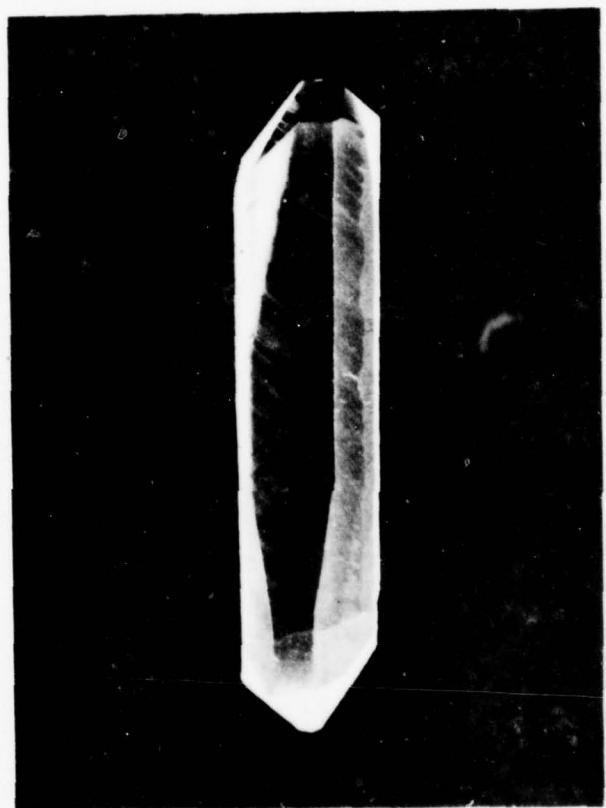
FIGURE 9. Photograph of SC-Bar of Cultured Quartz.

12

Figure 10 depicts a doubly rotated BAW plate with bulk wave propagation shown taking place in the thickness direction. A SBAW plate is shown adjacent. The propagation direction for the SBAW is shown between the IDTs to be along X_2'', i.e., parallel to the BAW propagation direction. This leads to a simple receipt whereby already-known results for doubly rotated BAW plates can be used to determine the approximate behavior of the "corresponding" SBAW plate. From the figure it is seen that the plate that corresponds to the $(YXw\ell)\emptyset/\theta$ BAW plate is a plate of orientation $(YXw\ell w)\emptyset/(\theta+90^{\circ})/\psi$. Notice that $\emptyset$ is the same for both plates. Also notice that θ need only be replaced by $\theta+90^{\circ}$ (keeping the result in the range $|\theta| \leq 90^{\circ}$).

It will be further seen that the rotational symbol of the SBAW plate describes a triply rotated cut. The third angle, given as ψ in Figure 10 permits the specification of a whole family of SBAW plates for each corresponding BAW plate, allowing one to optimize some parameter of operation such as temperature coefficient, coupling factor or beam steering angle. Because the SBAW mode most adapted to satisfying the traction-free boundary conditions on the crystal surface is the horizontally polarized shear mode, ψ can be chosen so that the $X_1'' - X_2''$ surface is along the direction given by the particle motion for one of the shear waves propagating along X_2'' in an unbounded medium. This enhances the ease with which the mode can propagate, and the cleanliness of the resulting mode spectrum.

The triply rotated cut angles $\emptyset/\theta/\psi$ can be reduced readily to an equivalent doubly rotated set by the formulas of spherical trigonometry; doubly rotated plates are the most general type of cut.

The doubly rotated BAW cuts in quartz have been mapped for f-T behavior in the entire $\emptyset/\theta$ plane[40]. An altitude chart of the first-order temperature coefficient frequency for the slower shear mode (the so-called c-mode) is given in Figure 11. This quantity corresponds to the slope of the f-T curves in Figure 5 at room temperature. By changing the ordinate scale from θ to $(\theta + 90^{\circ})$ one has the TC altitude chart, in first approximation, for doubly rotated SBAW plates for the slow-shear mode. Figure 12 gives the altitude chart for the faster shear mode (b-mode).

In general, all three of the wave types that exist for plane wave propagation in an unbounded medium exist and propagate in an SBAW plate, although their properties are modified by the finite boundaries. The quasi-longitudinal ("a" mode), and the two quasi-shear waves ("b", and "c" modes) are shown by their spectrographic responses for a plate $(YXw\ell)\emptyset=10^{\circ}/\theta=+34^{\circ}$ in Figure 13. Here the faster shear wave ("b" mode) is more strongly driven, because of its higher piezoelectric coupling, and also because its motion more nearly coincides with the direction of the surface of the plate, than the slower ("c") mode. By calculating the properties of a BAW plate having $\emptyset = 10^{\circ}$ and $\theta = -54^{\circ}$ one may get an approximate idea of the parameters of SBAW propagation in the $\theta = +34^{\circ}$ plate. Some of these are shown in Table 3. The top row gives the frequency constant N (one half the acoustic wave velocity); the second row gives the piezoelectric coupling for BAW propagation; the first order TC of frequency is shown in row three, and the calculated frequency response of a particular IDT is given in the last row. The mode strengths and frequencies are to be compared with those in Figure 13, where it is seen that the agreement is quite good. In Figures 14, 15, and 16 are given curves of N (the frequency constant), $|k|$ (the piezoelectric coupling), and T_f (the first order TC of frequency) for quartz BAW propagation for cuts $(YXw\ell)$ $\emptyset = 0^{\circ}(6^{\circ})$ $30^{\circ}/\theta$.

13
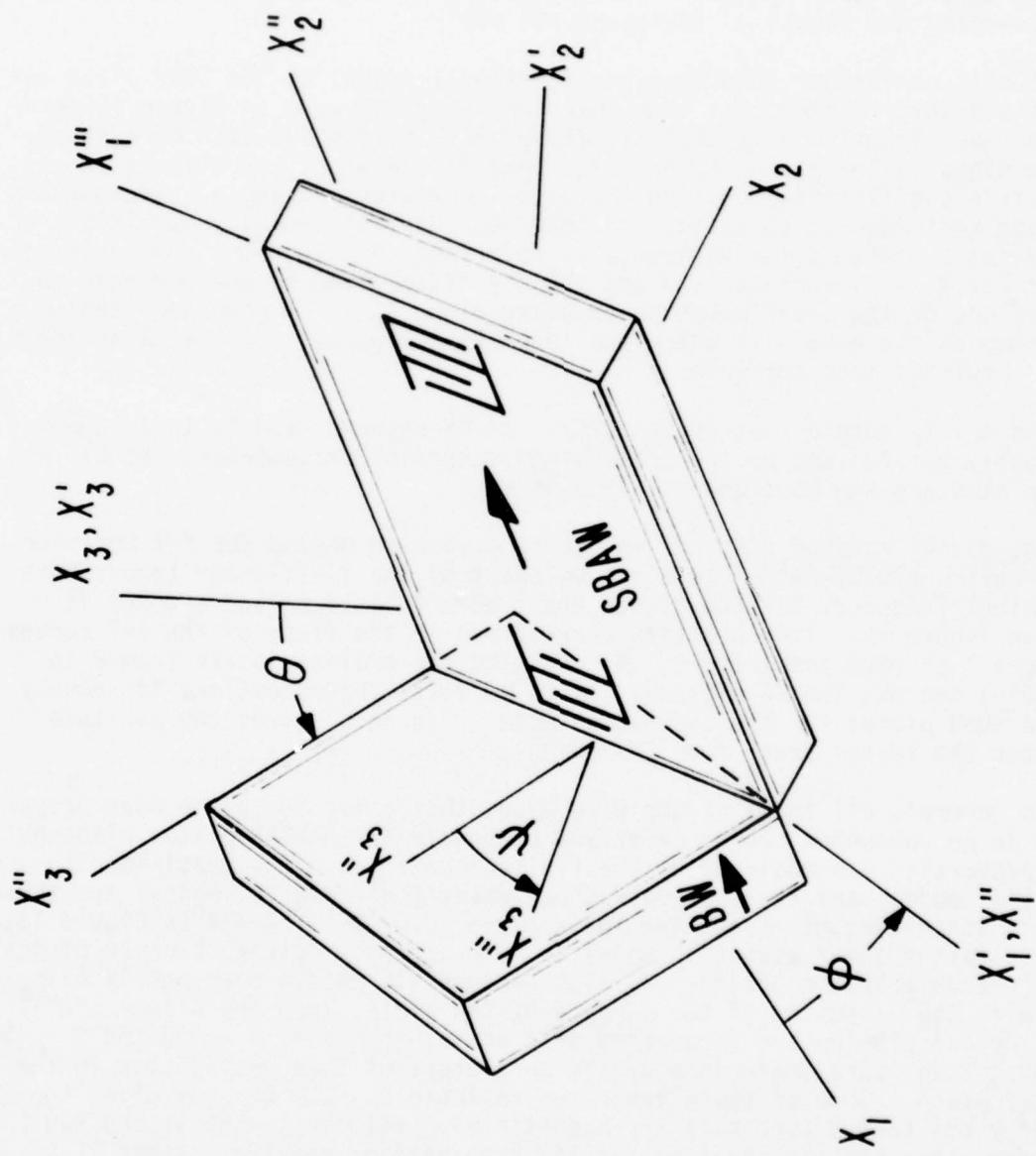
FIGURE 10. Doubly Rotated BAW and Triply-Rotated SBAW Plates.
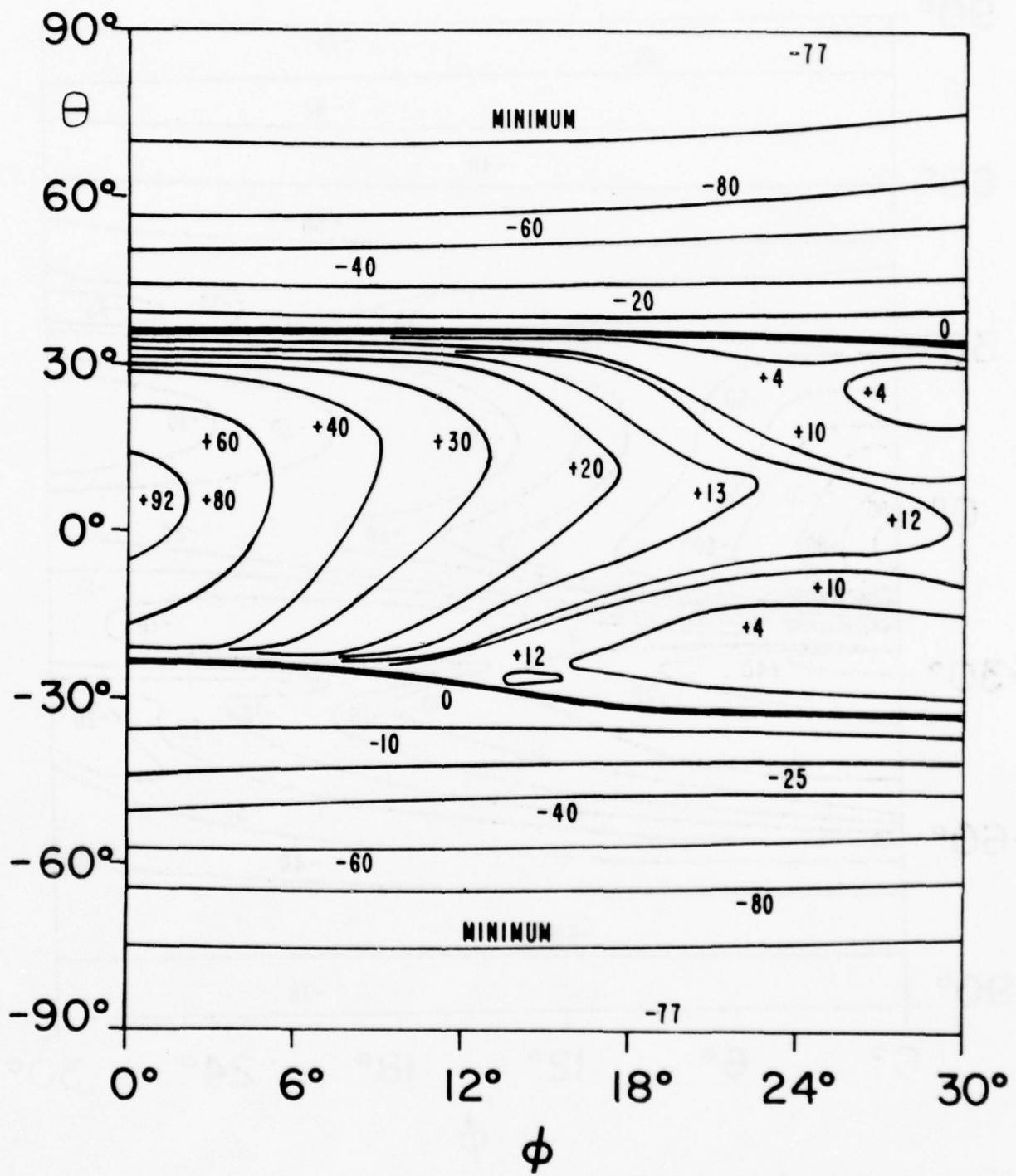
FIGURE 11. Altitude Chart of T_f (mode c) in Quartz.

15
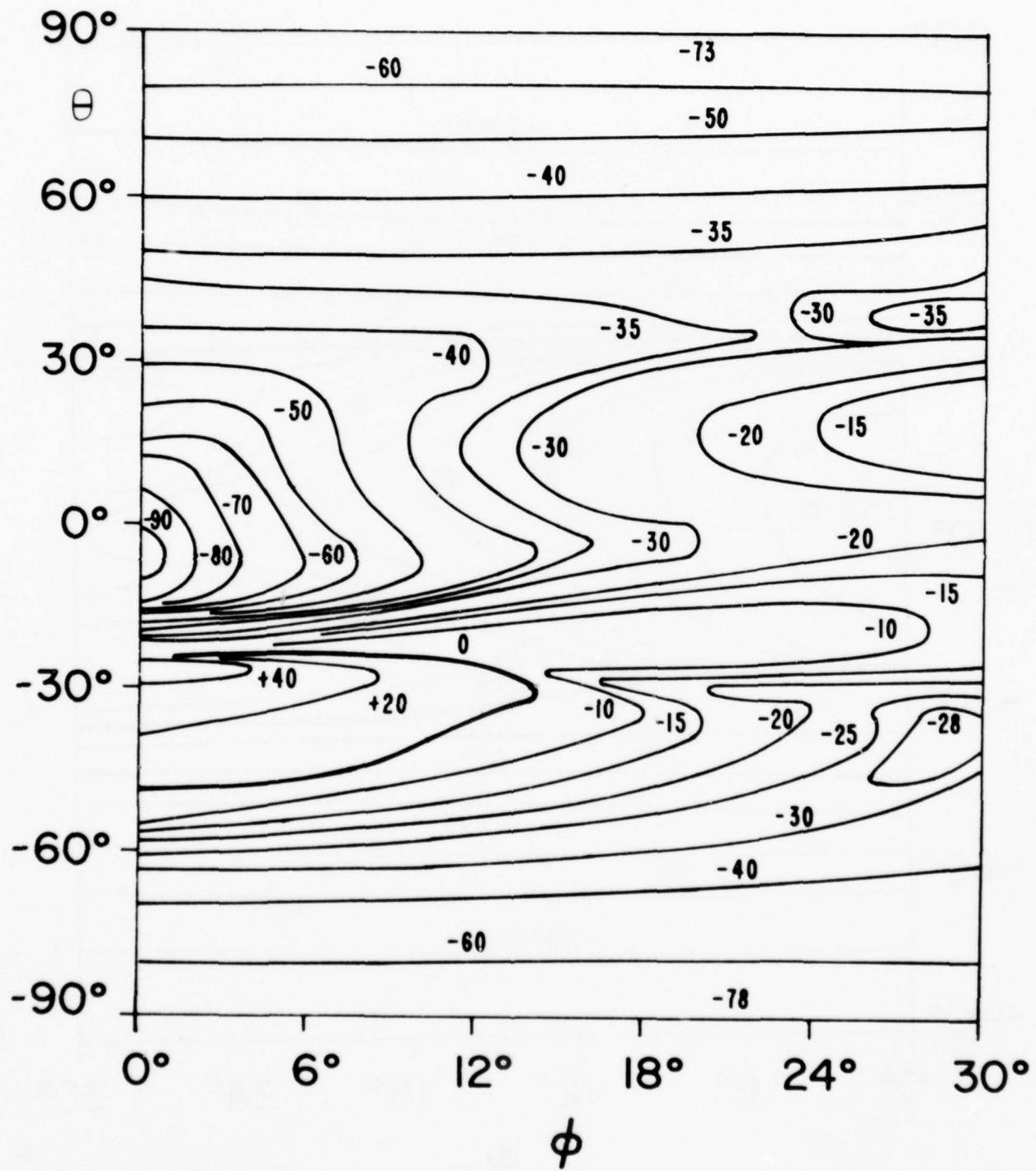
FIGURE 12. Altitude Chart of T_f (mode b) in Quartz.

16
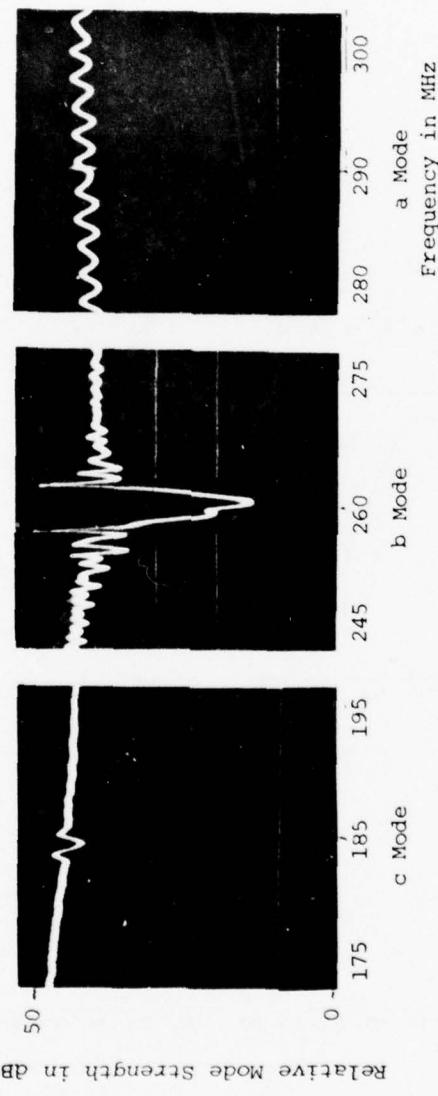
SBAW MODE SPECTROGRAPH OF DOUBLY ROTATED QUARTZ PLATE.

FIGURE 13. Spectrographs of Three SBAW Modes.

17
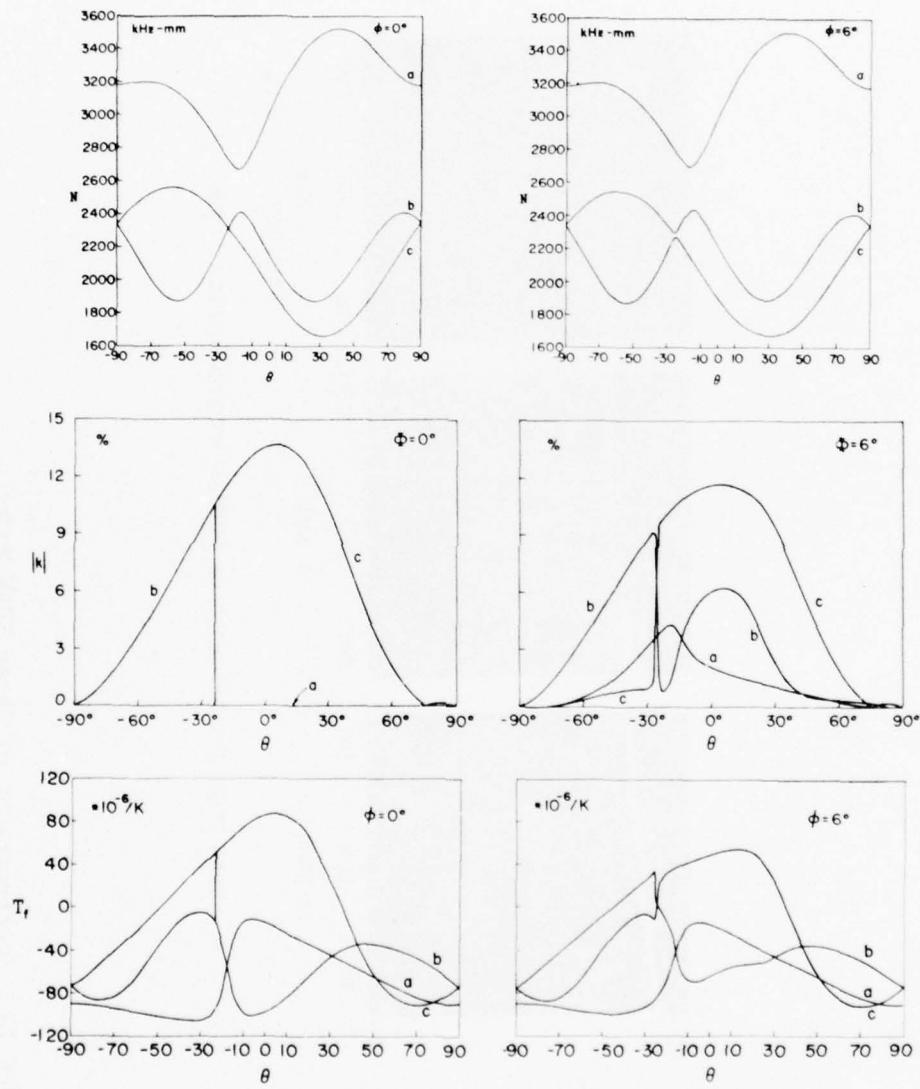
FIGURE 14. N, |k|, and T_f for $(YX\omega\ell)0°$, $6°/\theta$ Quartz Cuts.
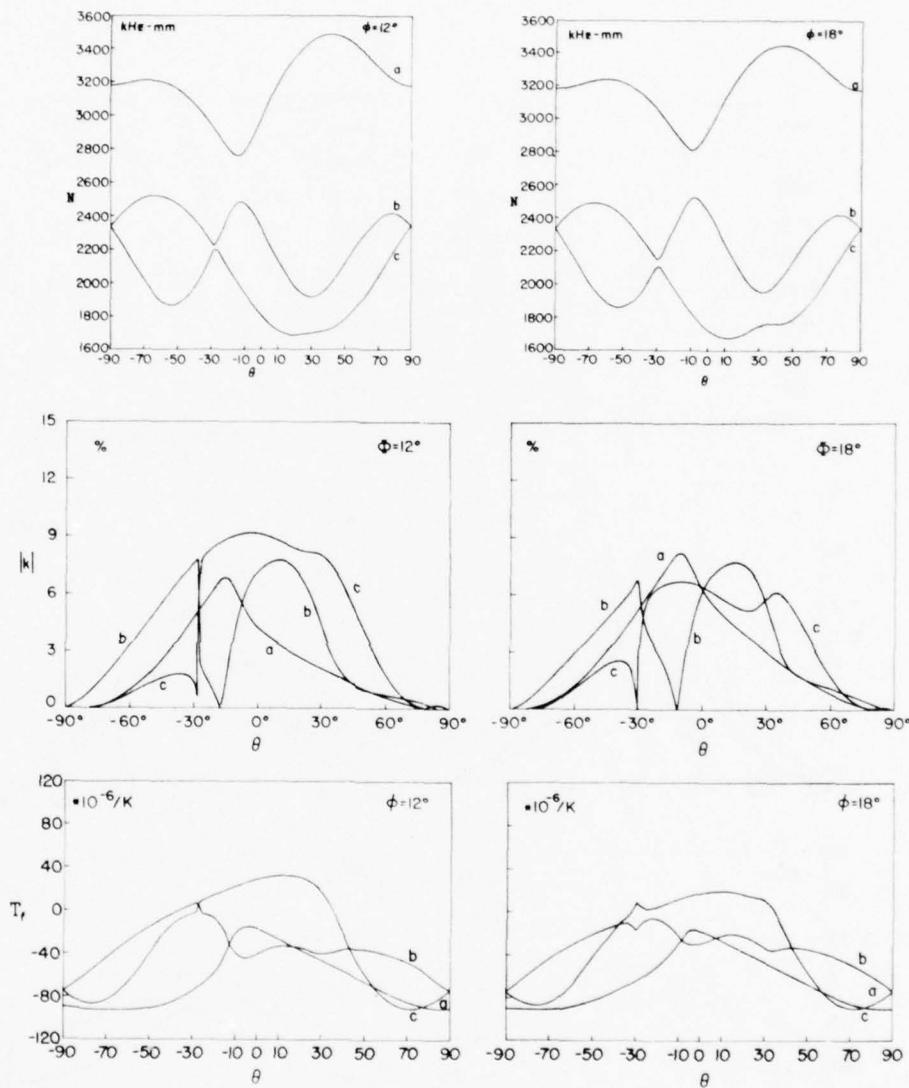
FIGURE 15.   N, |k|, and T_f for (YXwℓ)12°, 18°/θ Quartz Cuts.

19
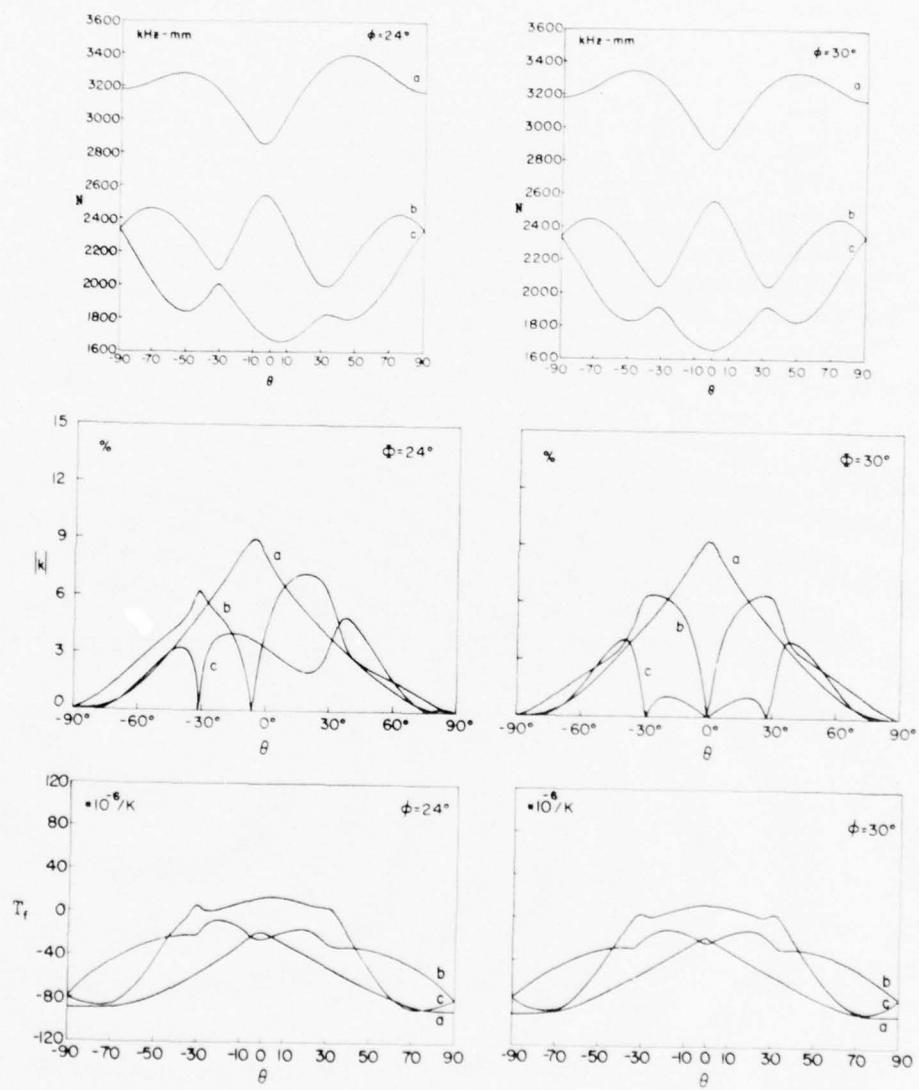
FIGURE 16.   N, |k|, and T$_f$ for (YXℓt)24°, 30°/θ Quartz Cuts.

20

TABLE 3.   Shallow Bulk Acoustic Mode Properties

(YXwℓ) ∅ = 10° / θ = +34°; Z-Propagation SBAW

	MODE c	MODE b	MODE a
N (m/s)	1873	2521	3177
(K) %	0.78	3.77	1.04
T_f (10^{-6}/K)	-56.0	-20.2	-94.6
f(MHz)	185.3	249.4	314.3

Certain orientations in quartz should be avoided. These include BAW plates (and their corresponding SBAW cuts) of orientations near ∅≈0°, θ ≈-24° and ∅ ≈10.4°, θ ≈-26.6°. Both of these directions are directions of degeneracy, where the two shear velocities coincide; near these points the energy flux deviations are large.

PIEZOELECTRIC TRANSDUCTION

Transduction of acoustic waves via the piezoelectric effect may be determined if the forces produced are known. The force densities are given by the stress-gradients, which, in turn, are brought about by the electric fields produced by the IDT array[44]. The piezoelectric portion of the mechanical stress relation is

$$T_{ij} = - e_{kij} E_k .$$ (2)

The mechanical force-densities F_j are then

$$F_j = - e_{kij} E_{k,i} .$$ (3)

IDT fingers produce electric fields E_k that are very sharply peaked at the electrode edges. An example is given in Figure 17, where is shown the static field parallel to, and at, the crystal surface, normalized to the field that would exist between parallel plate capacitors of equal gap; the field possesses branch-point singularities at each edge. The other field components behave in a similar manner. Because of the spikes in E_k, the force densities can be represented, to an excellent approximation as delta-functions, and the excitation of acoustic waves evaluated in a straightforward manner[45].

Taking as an example a rotated-Y-cut of quartz of orientation (YXℓ)θ, with an IDT array along X_1, the electric field gradients peak sharply at the electrode finger edges, and are $E_{1,1}$ (largest) and $E_{2,2}$ plus both $E_{2,1}$ and $E_{1,2}$. The rotated piezoelectric constants that are non-zero are e'_{111}(≡e_{111}), e'_{122}, e'_{133}, e'_{123}, e'_{213} , e'_{212}, e'_{313}, and e'_{312}. Therefore $E_{1,1}$ produces

21
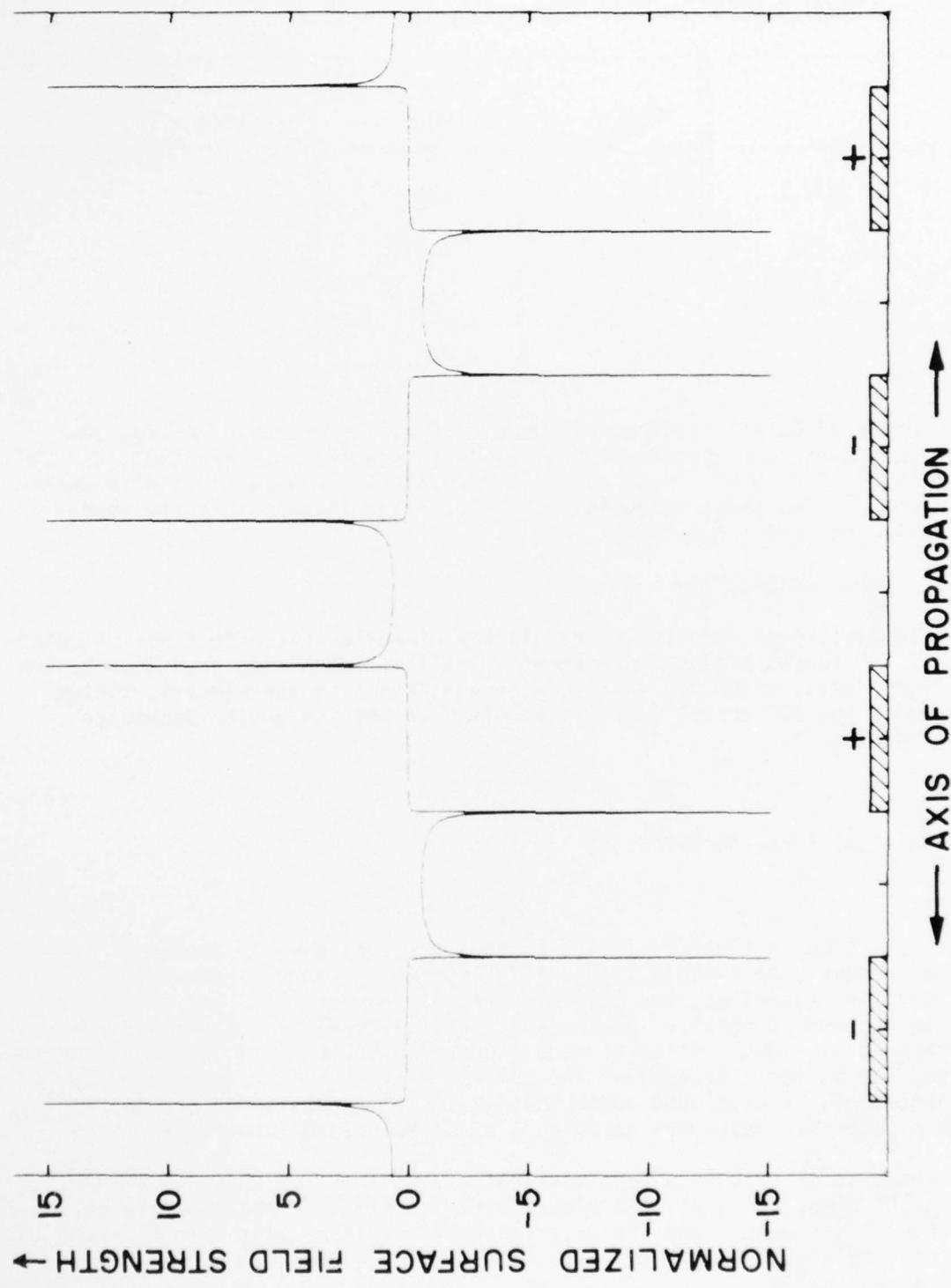
FIGURE 17. Static Electric Field Distribution for IDTs .

X_1 directed forces, but no forces along X_2 or X_3. $E_{2,2}$ likewise generates X_1 forces. The weaker gradients $E_{2,1}$ and $E_{1,2}$ both produce X_3 and X_2 forces. The X_1 and X_2 forces lead to SAWs.

If the IDT array is rotated so that the finger edges are parallel to the X_1 axis and propagation takes place along X_3, then E_1 vanishes, along with the gradients $E_{2,1}$ and $E_{3,1}$. The gradients $E_{2,2}; E_{2,3}; E_{3,2} and E_{3,3}$ all produce forces directed along X_1 but no other component of force. SAW propagation cannot take place but an SH-type of BAW propagates, and this is the SBAW that has been investigated to date.

A similar calculation shows that for rotated-X-cuts of crystals in class 32 (quartz, aluminum phosphate), SBAW propagation along any direction parallel to the free surface produces SAW generation as well. Again, for rotated-X-cuts of class 3m, both SBAW and SAW are generated for any propagation direction parallel to the plate surface.

It appears, then, that a rather elementary consideration based on the piezoelectric relations and the delta-functions produced by the IDT array yields valuable insight into the production of acoustic waves in piezo crystals. This approach can readily be placed on a quantitative basis. Another result of the delta-function model of transduction is the realization of SAW and SBAW equivalent circuits in the analog form shown in Figure 18. The piezo-transformers are placed at the locations of the electrode edges. Unattached electrodes are simply left unconnected to the supply voltage.

TRAPPING/DUCTING

Energy trapping was applied to BAW plates by Mortley[46-49], Shockley, et al.[50,51], and Mindlin[52]. Trapping or ducting of SAWs has been treated by Oliner[53], Ash, et al.[54], and Tiersten, et al.[55-57]. It was suggested for SBAW by Lewis[13], and experimentally proven by Kagiwada, et al.[23,26].

The periodic perturbations resulting from the unconnected metallic electrodes placed in the SBAW path produce the ducting effect by a combination of mass-loading and piezoelectric effects. The SBAW wave becomes analogous to a Love wave - a horizontally polarized shear wave that requires a discontinuity or material gradient in the depth direction for propagation.

For untrapped SBAW propagation, the transmission lines in Figure 18 are non-uniform in their characteristic impedance and propagation wavenumber; the use of a ducting structure renders the lines uniform.

In Figure 19 is shown an energy-trapped SBAW narrow-band filter on ST-cut quartz[26]. It is seen how extremely clean the mode spectrum is, resulting from the absence of SAWs; this is further borne out by the broad frequency sweep of the same filter[24] shown in Figure 20.

RADIATION FIELD

SBAW radiation patterns have been very successfully calculated on the basis of simple antenna theory by Lewis[13,58], and on the basis of more extensive calculations by Jhunjhunwala, et al.[31], and Lee[32]. Results of an exact calculation for the rotated-Y-cuts of quartz excited by a single infinite line source are given by Kagiwada, et al., and are shown in Figure 21 for the

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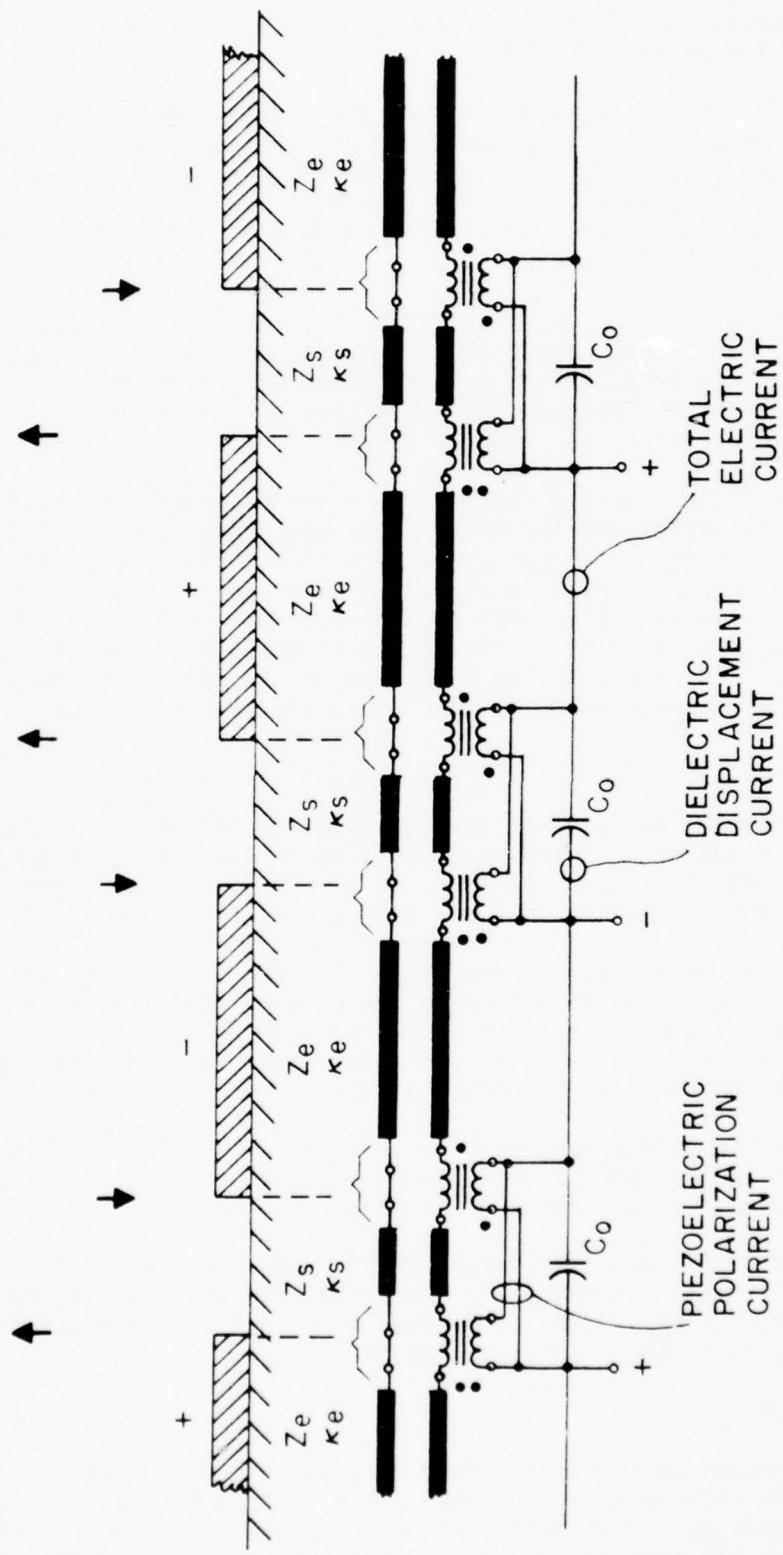
FIGURE 18. Equivalent Network for SBAW Transmission.

24
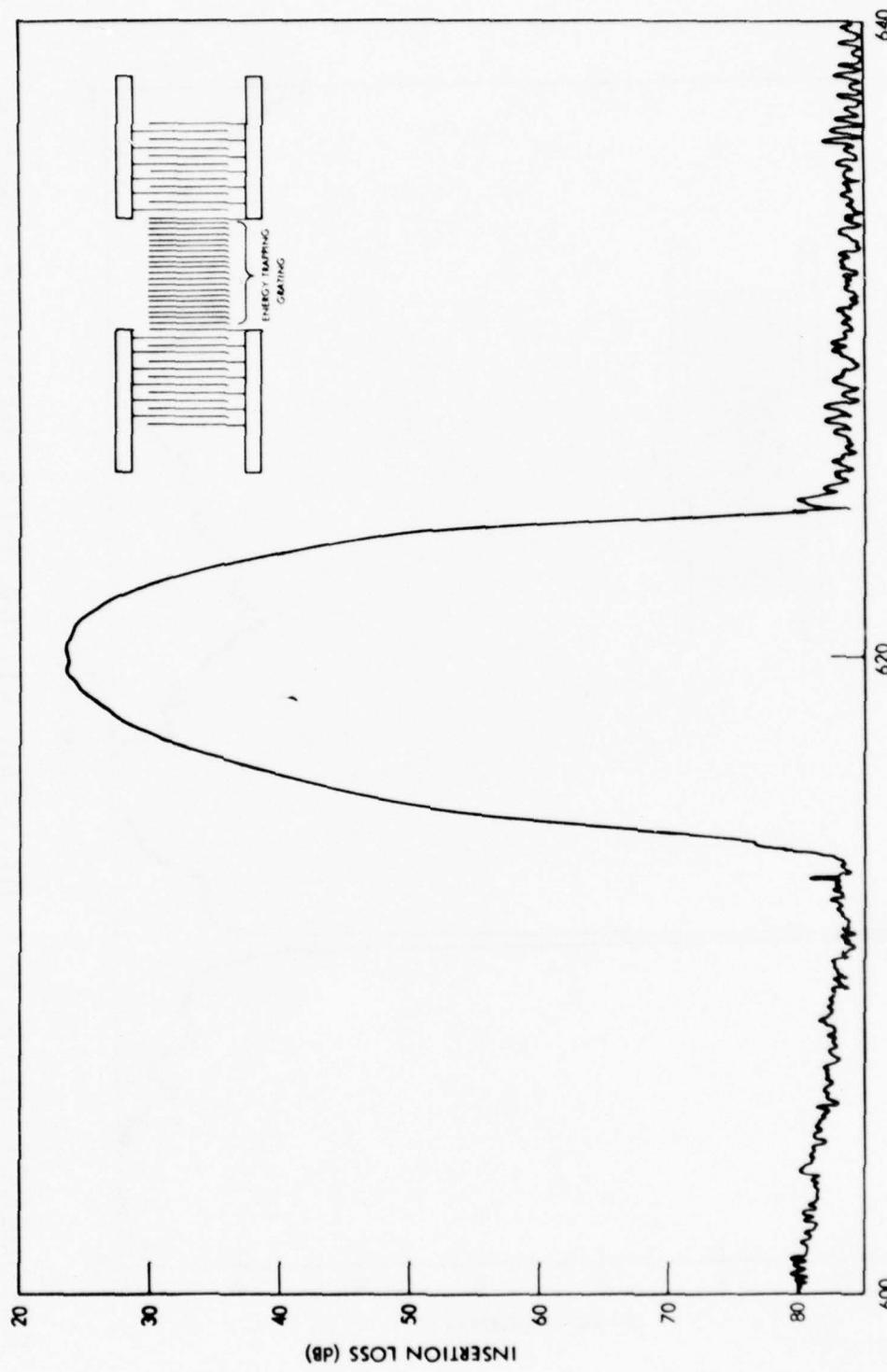
FREQUENCY RESPONSE OF SBAW FILTER WITH METALLIC GRATING

FIGURE 19. Narrowband Response of Bandpass SBAW Filter.
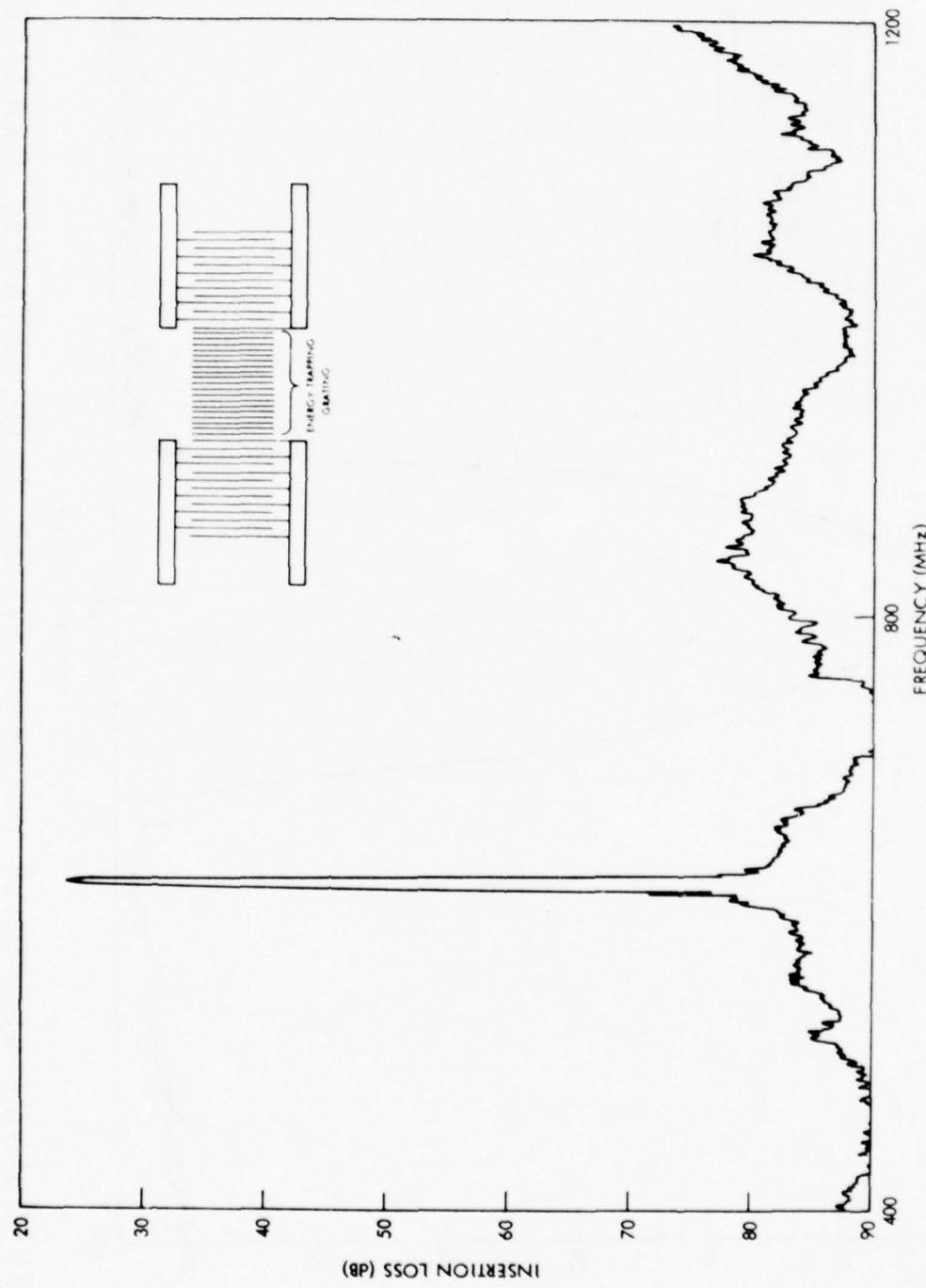
FREQUENCY RESPONSE OF SBAW FILTER WITH METALLIC GRATING

FIGURE 20.   Wideband Response of Bandpass SBAW Filter.

| CUT	$\theta°$	CURVE
AT	+35.25	·······
BT	−49.00	— — —
ST	+42.75	———

10dB

X_3

X_2'

θ

X_2
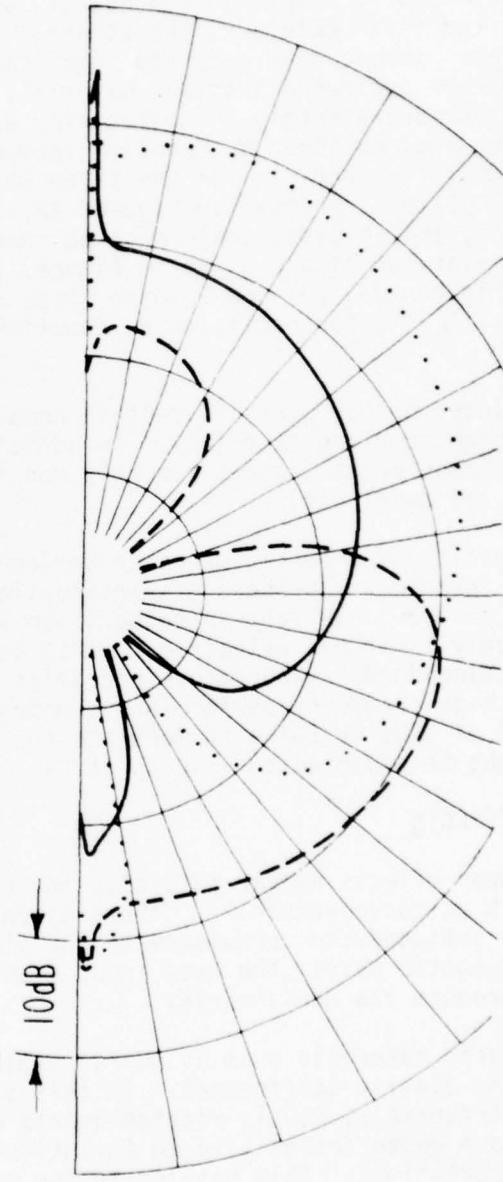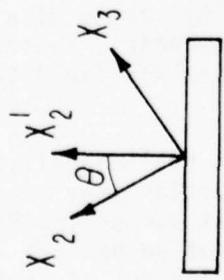
FIGURE 21. Far-Field Radiation Pattern of SBAW on (YXℓ)θ Quartz.

27

AT, BT, and ST cuts[27]. The plots are of relative radiated power in the far field. It is seen how dramatically the pattern varies with θ even between the adjacent AT and ST cuts. Further work will possibly make use of Z-transforms[59-61], modified to account for the anisotropy of the medium, to predict accurately the radiation from IDTs.

NEW MATERIALS

Two areas of future device potential appear to be (1) materials with higher piezoelectric coupling than quartz, and (2) semiconducting piezoelectrics. In the first category, the strongly piezoelectric substances lithium tantalate and niobate have received some attention. Aluminum phosphate (berlinite) appears another attractive material; it has the same crystal class as quartz but is more strongly piezoelectric, as well as possessing a zero TC locus. Frequency constant N, coupling factor $|k|$, and first order temperature coefficient of frequency T_f for the three modes of infinite singly and doubly rotated BAW plates are shown in Figures 22, 23, and 24. To convert to SBAW orientations, the abscissa scale must be changed as discussed in prior sections. Similar curves are given in Figures 25, 26, and 27 for lithium tantalate, and Figures 28, 29, and 30 give these quantities for lithium niobate. The locus of T_f = o for berlinite as function of angles Ø and θ is given in Figure 31.

As pointed out by Lewis[16], certain complications appear for SBAW propagation in high coupling materials. In addition, the electric field pattern at the electrode edges becomes strongly modified and has to be taken into account in the model used[45].

Propagation of acoustic waves in semiconductors appears to be an attractive way to further the process of miniaturization of microelectronic signal processing devices. Gallium arsenide is an excellent candidate material because not only is it piezoelectric, but it possesses a large bandgap, allowing high semiconductor temperature operation, as well as large mobility values, leading to high frequency performance comparable to SAW capabilities. Using the passage of SAWs or SBAWs to modulate the active regions of semiconductor devices might be expected to lead to attractive new IC-compatible devices.

NONLINEAR EFFECTS

Nonlinear effects appear naturally in certain acoustic signal processing devices such as convolvers[62,63]. These operate by virtue of a nonlinear effect in the semiconductor proximate to the piezoelectric substrate that supports the acoustic wave; the wave induces an electric field in the semiconductor to produce the nonlinearity.

Dielectric materials such as quartz exhibit nonlinearities as well, primarily in the elastic stiffnesses. In this situation they are usually undesirable. Fortunately, doubly rotated quartz cuts supporting BAWs have been found that are quite insensitive to the effects of mechanical stress effects of various sorts[41,64]. This has led to the development of resonators that have very good resistance to mechanical shocks and electrode film stress changes. Closely related to this problem is that of frequency changes in BAW resonators due to abrupt temperature changes. Once again, doubly rotated quartz cuts have been found where this nonlinear elastic effect is minimized[65].
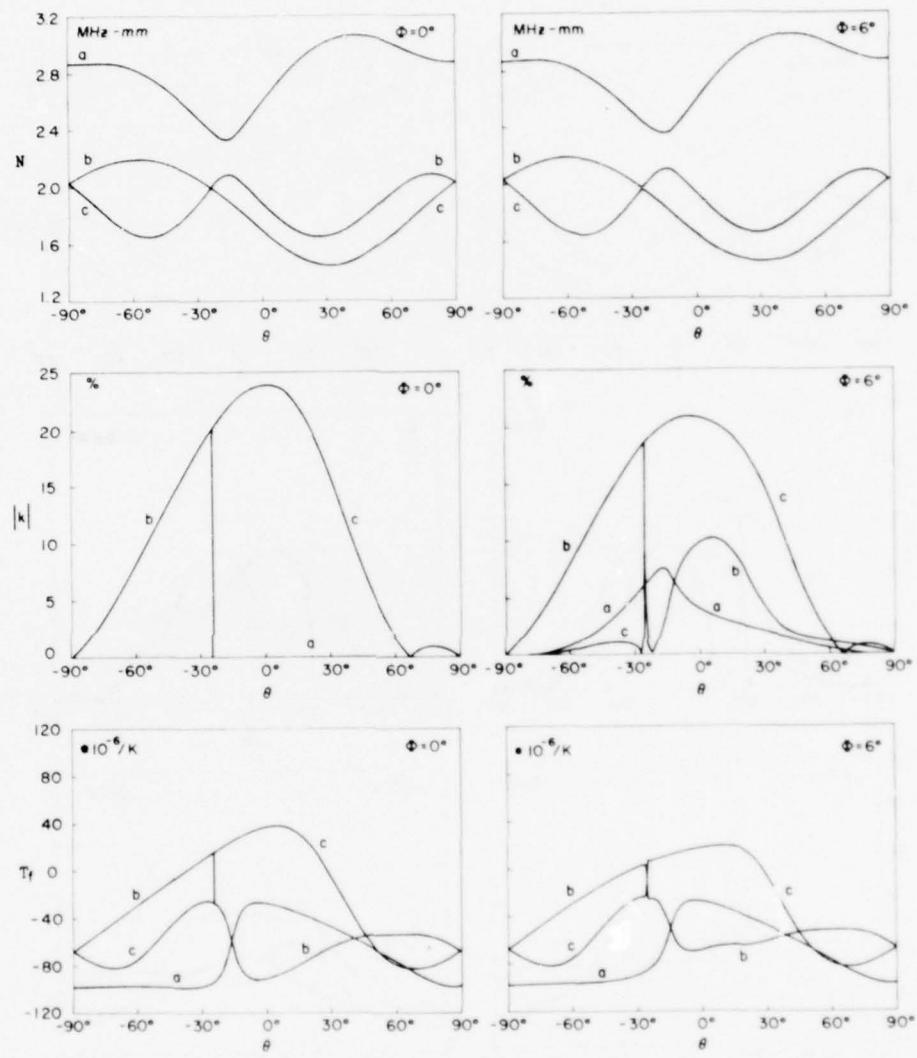
FIGURE 22. N, |k|, and T_f for $(YX_{wt})0^\circ$, $6^\circ/\theta$ Berlinite Cuts.
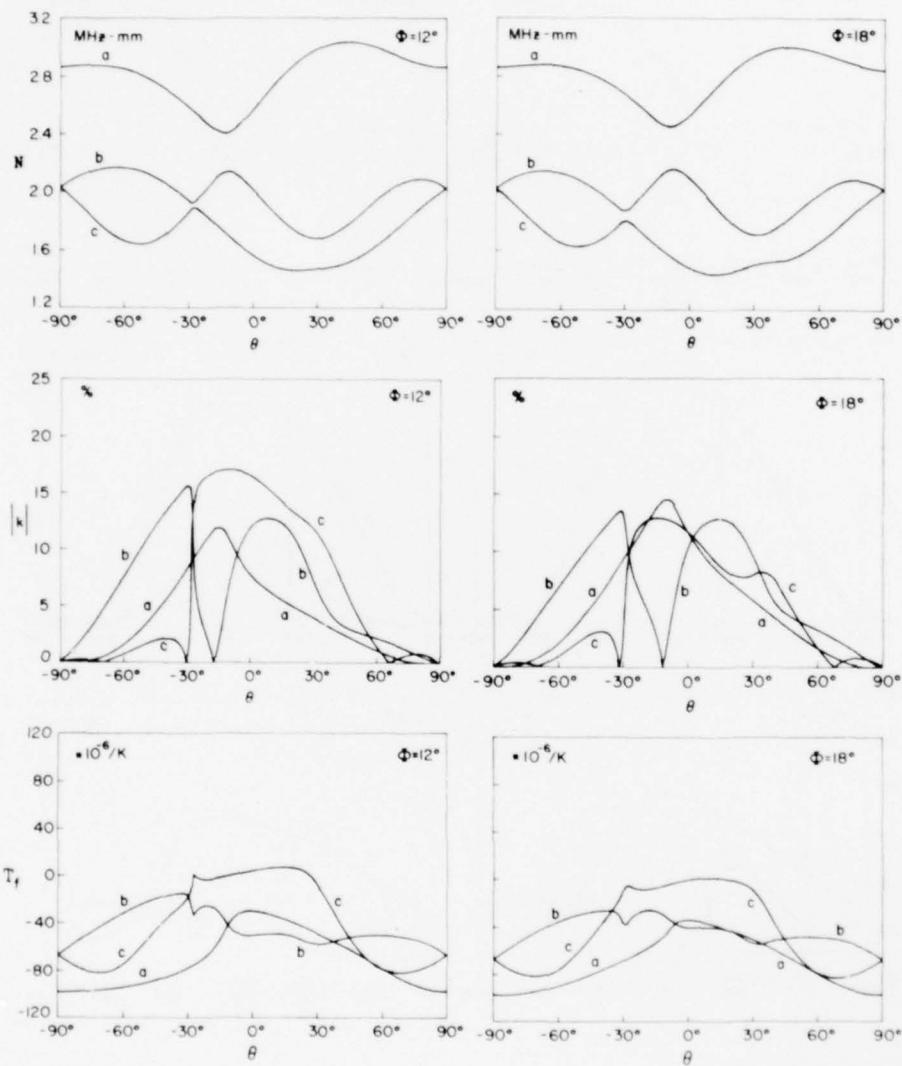
FIGURE 23.   N, |k|, and T$_f$ for (YX$\omega\ell$)12°, 18°/θ Berlinite Cuts.

30
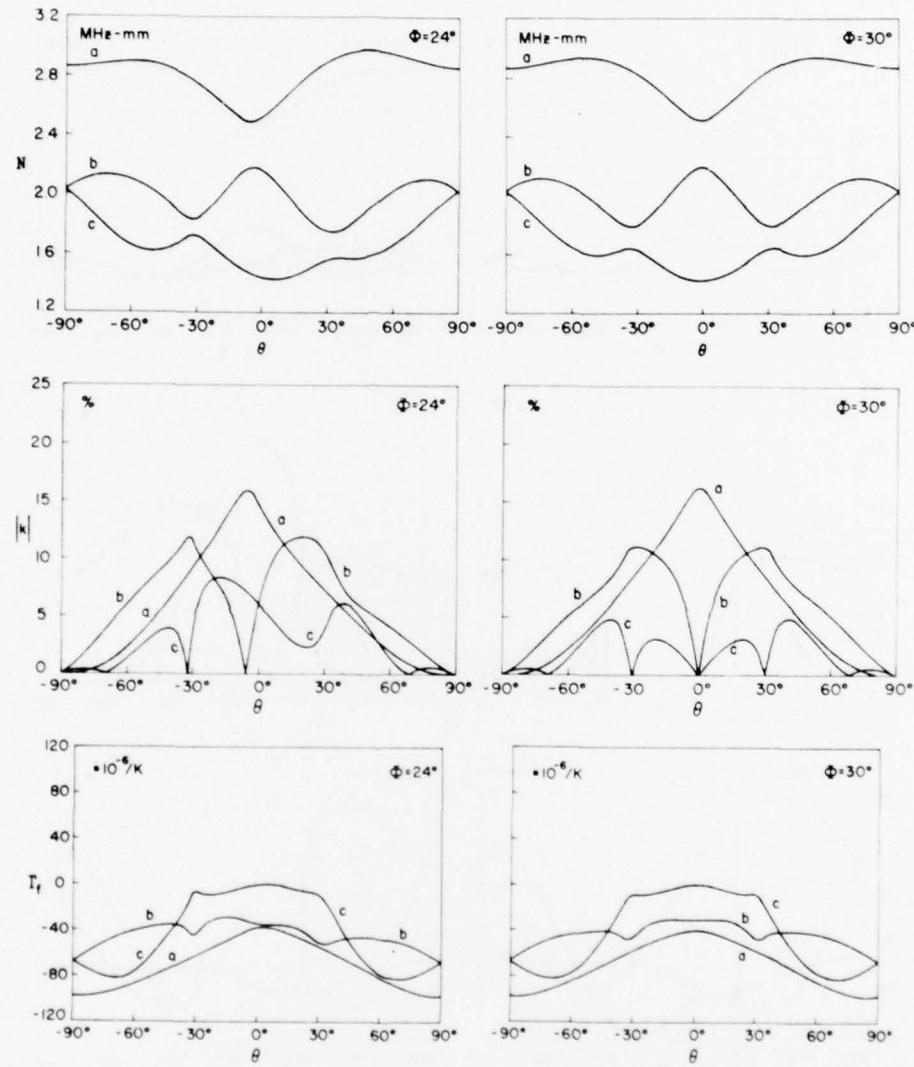
FIGURE 24. N, |k|, and T_f for (YX$\omega\ell$)24°, 30°/θ Berlinite Cuts.
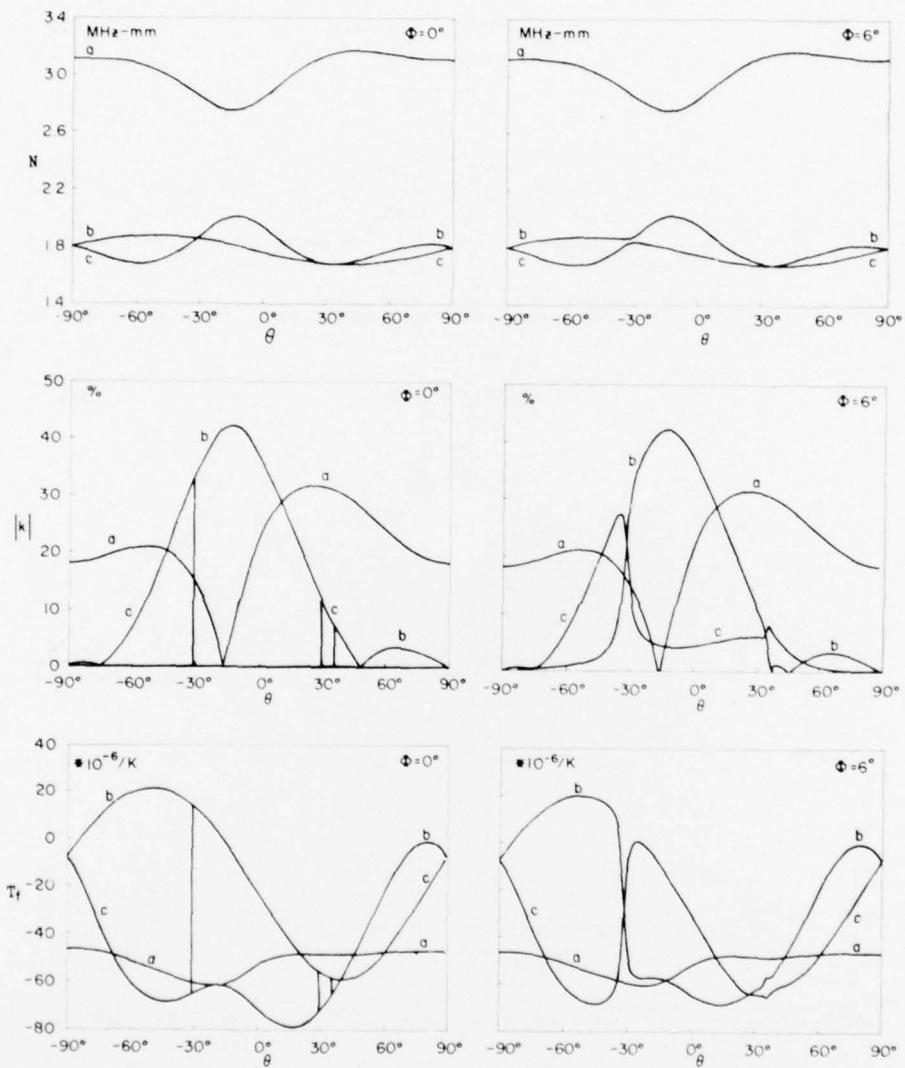
FIGURE 25.   N, |k|, and T_f for (YXwl)0°, 6°/θ LiTaO$_3$ Cuts.

32
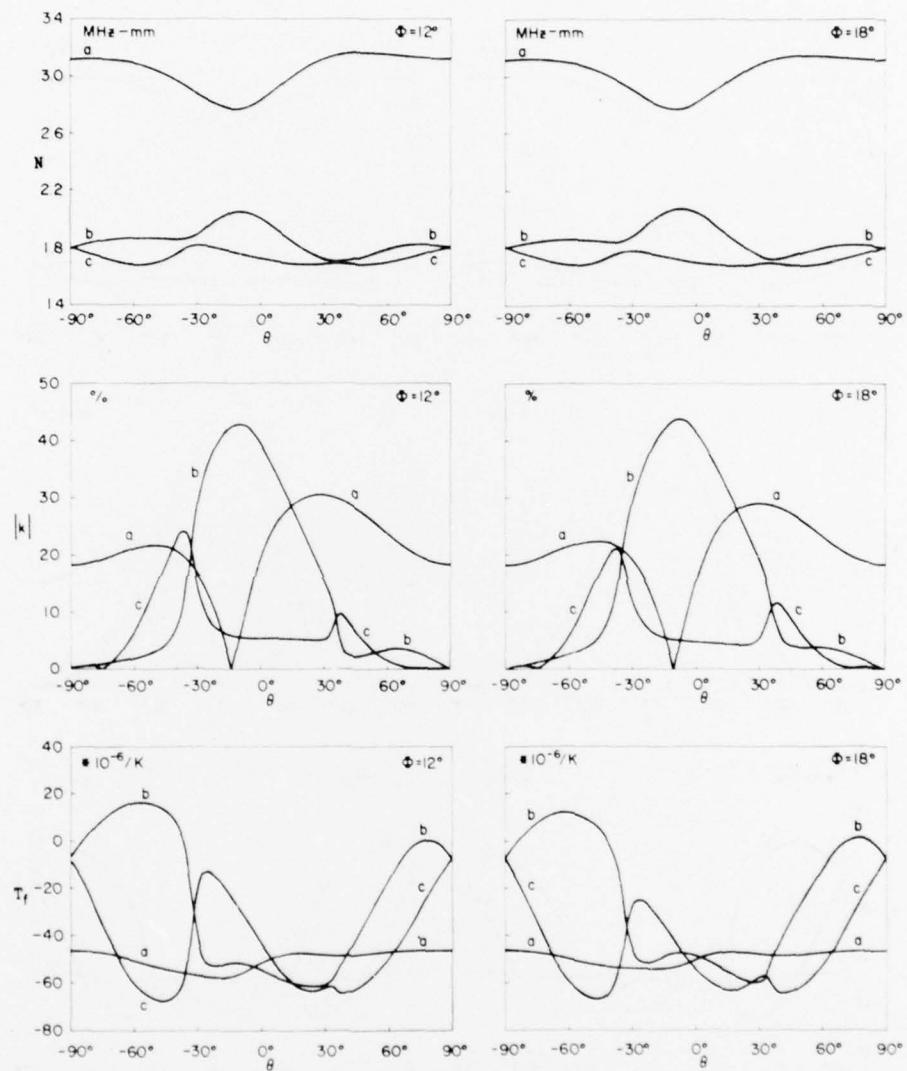
FIGURE 26. N, $|k|$, and T_f for $(YX\omega\ell)12°$, $18°/\theta$ LiTaO$_3$ Cuts.
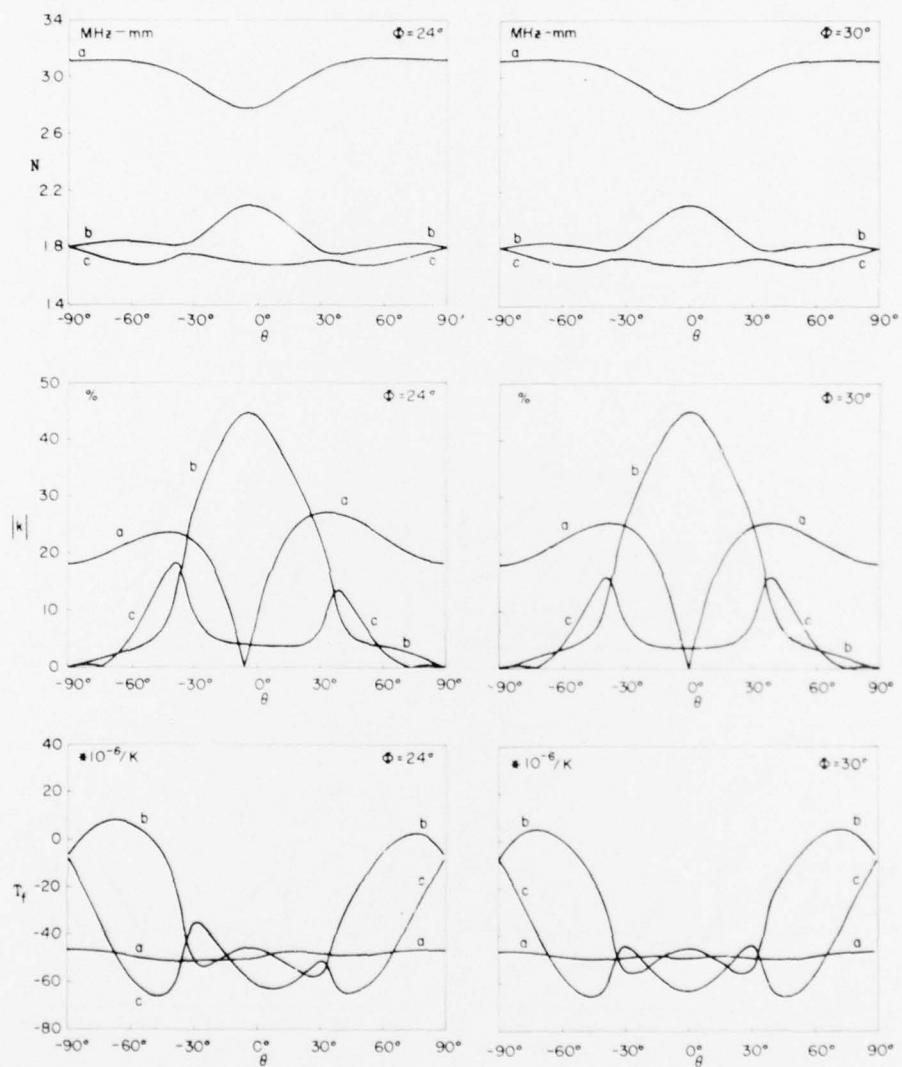
FIGURE 27. N, |k|, and T_f for (YXwl)24°, 30°/θ LiTaO₃ Cuts.

34
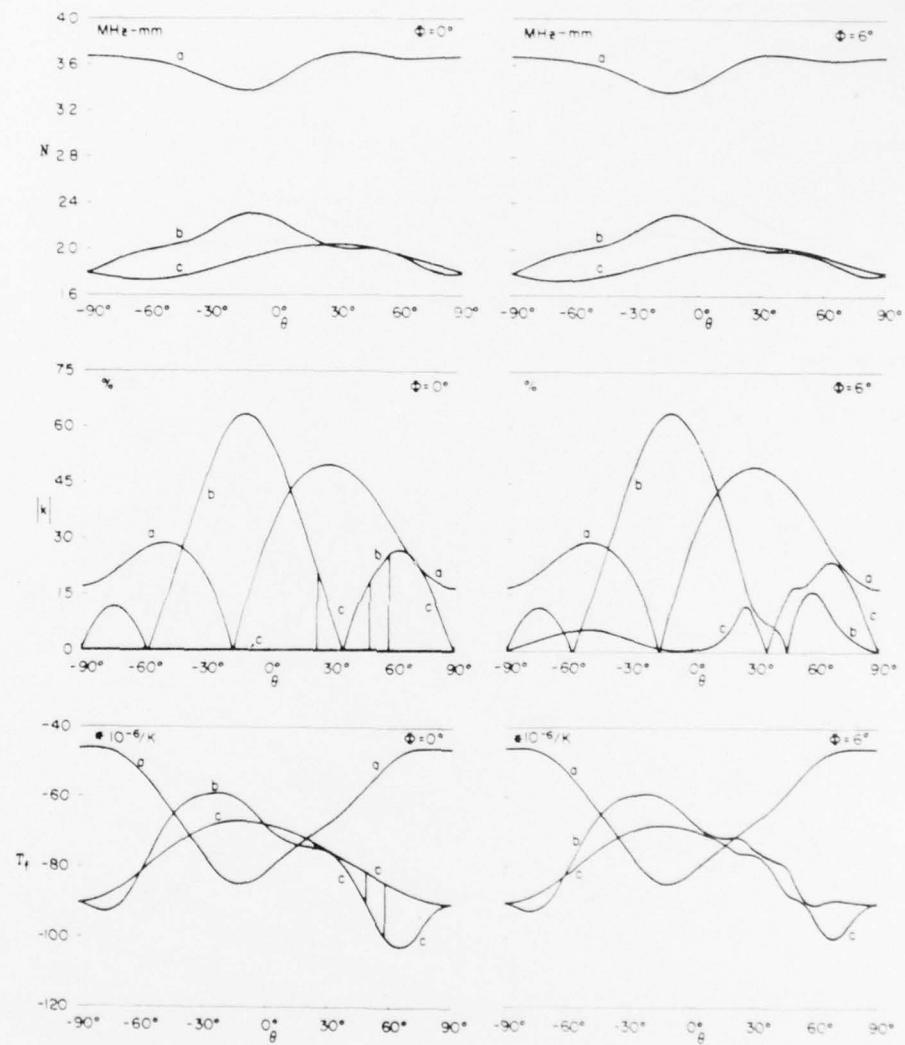
FIGURE 28. N, |k|, and T$_f$ for (YX⍀)0°, 6°/θ LiNbO$_3$ Cuts.
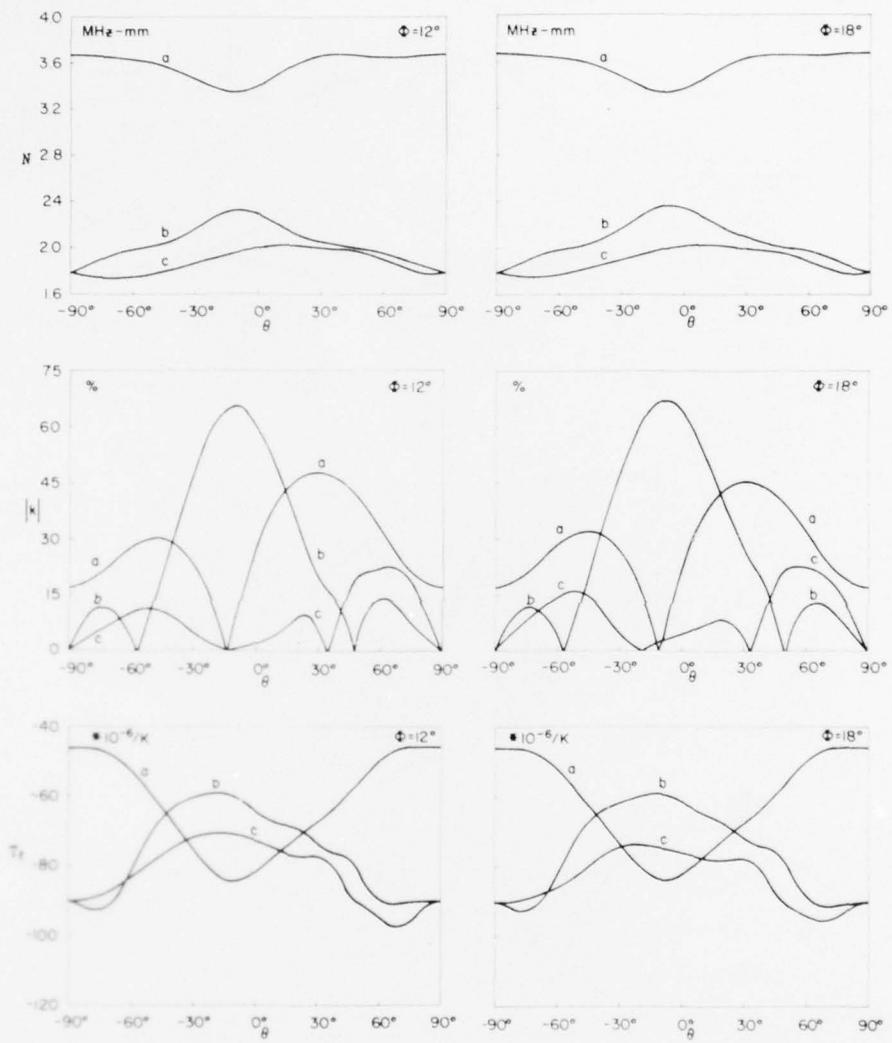
FIGURE 29. N, |k|, and T_f for (YXωℓ)12°, 18°/θ LiNbO$_3$ Cuts.
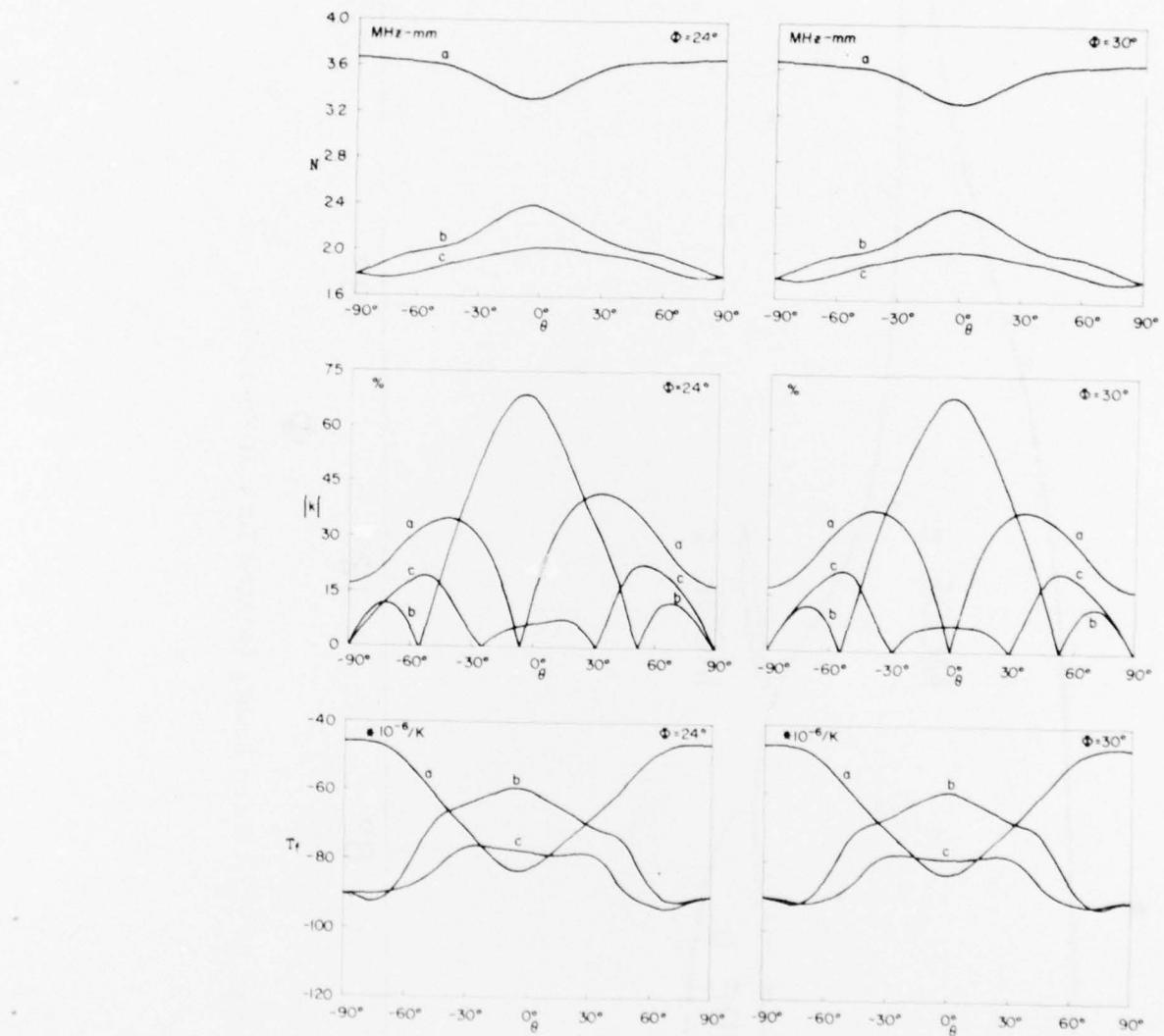
FIGURE 30. N, $|k|$, and T_f for $(YX_{wl})24°$, $30°/\theta$ LiNbO$_3$ Cuts.

37
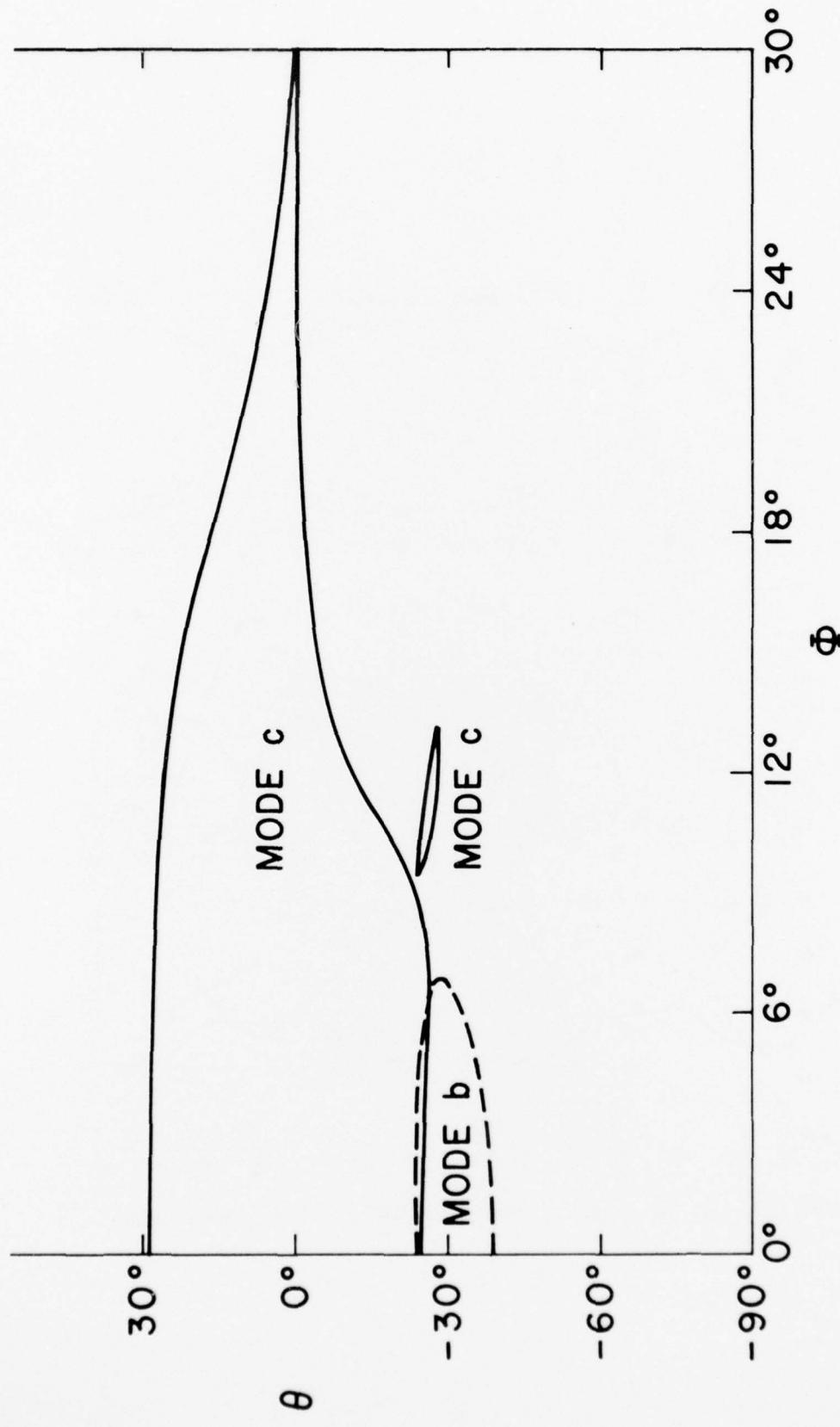
FIGURE 31. Locus of $T_f = 0$ for Doubly Rotated Cuts of Berlinite.

These BAW successes naturally lead one to hope that analogous SAW and SBAW cuts exist; if they do, it is logical to look for the SBAW cuts according to the prescription given above, viz., keeping $\emptyset$ fixed, and changing θ to $\theta+90^0$. The additional angle ψ, shown in Figure 10, can be adjusted for best $\overline{TC}$ or transduction efficiency.

Lewis[58] has observed non-linear interactions between SAW and SBAW in a variety of substrates.

MATERIAL ATTENUATION

The room temperature attenuation of acoustic waves in a crystal is a function of the viscosity coefficients of the material, and has been calculated for BAW waves in quartz[41]. This intrinsic loss becomes important in the GHz range in quartz. A more severe restriction on the attenuation of GHz devices may be due to scattering losses due to etch channels[66]. These arise from chemically polishing the substrate when the source material contains impurities and dislocations; they may be largely removed by using electrically swept material.

CONCLUSION

This report has described recent work in the area of shallow bulk acoustic waves, and has extended the applicability of bulk acoustic wave calculations to this newer type of wave propagation by giving simple rules whereby approximate results may be obtained for SBAW using BAW analyses. Both singly and doubly rotated plates have been considered, as have materials other than quartz.

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